AD NUMBER

AD142275

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; Apr 1958. Other requests shall be referred to Aeronautical Systems Div., Wright-Patterson AFB, OH 45433.

AUTHORITY

ASD USAE ltr, 9 Jun 1972

WADC TECHNICAL REPORT 57-1
VOLUME II
ASTIA Document No. AD142275

ETL

TECHNIQUES FOR APPLICATION OF ELECTRONIC COMPONENT PARTS IN MILITARY EQUIPMENT

VOLUME TWO

Technical Writing Service
McGRAW-HILL BOOK COMPANY, INC.

April 1958

WRIGHT AIR DEVELOPMENT CENTER

Electronic Components Laboratory, Contract No. AF 33(616)-2815, Project No. 4155

WADC TECHNICAL REPORT 57-1
VOLUME II
ASTIA Document No. AD142275

TECHNIQUES FOR APPLICATION OF ELECTRONIC COMPONENT PARTS IN MILITARY EQUIPMENT

VOLUME TWO

POWER SOURCES and CONVERTERS FUSES and CIRCUIT BREAKERS ELECTRICAL INDICATING INSTRUMENTS PRINTED WIRING BOARDS SOLDER and FLUXES CHOPPERS BLOWERS RF TRANSMISSION LINES and WAVEGUIDES

CONSULTANTS

R. P. Lyon, General Electric Co.

W. H. Hannahs, Automatic Production Research

R. C. Hitchcock, Syntron Co.

J. H. Miller, Weston Electrical Instrument Corp.

Robert Milliron, Wright Air Development Center

Milton Tenzer, U. S. Army Signal Engineering Laboratories

ADVISORY STAFF

L. M. Clement
Office, Assistant Secretary of Defense

A. W. Rogers, Thomas M. Child
U. S. Signal Engineering Laboratories

E. A. Mroz
Bureau of Ships, Navy Department

Floyd Wenger
Air Research and Development Command

PROJECT ENGINEERS

Lt. E. R. Byrne, Lt. L. D. Smith, Lt. J. D. Wood, USAF, *Wright Air Development Center*

EDITORS

Keith Henney and Craig Walsh, *McGraw-Hill Book Company, Inc.*

Technical Writing Service
McGRAW-HILL BOOK COMPANY, INC.
April 1958

Electronic Components Laboratory, Contract No. AF 33(616) 7315, Project No. 4155

Wright Air Development Center
Air Research and Development Command, United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report constitutes the second of three volumes sponsored by the Electronic Components Laboratory, Directorate of Laboratories, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, under Task No. 41508 of Project No. 4155, "Improved Electronic Components." Gathering the raw material and reducing it to book form was carried out under Air Force Contract No. AF 33 (616)-2815. Volume I was published January 1957 as WADC Technical Report 57-1, ASTIA Document No. AD110672.

Throughout the period beginning 1 February 1955 and ending with the final production of this volume, the editors had the active and helpful participation of the Department of the Army, Signal Corps Engineering Laboratories, and Department of the Navy, Bureau of Ships, as well as the cooperation and advice of Lewis M. Clement, Office of the Assistant Secretary of Defense (AE); Floyd Wenger, Air Research and Development Command; E. A. Mroz, Bureau of Ships, Department of the Navy; and A. W. Rogers and Thomas M. Child, U.S. Army Signal Engineering Laboratories.

During the several phases of the project John Trader, Lt. Edward R. Byr[illegible], Lt. L. D. Smith and Lt. J. D. Wood acted as Project Engineers.

For the Technical Writing Service of the McGraw-Hill Book Company, [illegible]ith Henney, Craig Walsh, Harrison Eddins, Ronald Engleman, John [illegible]lick, Robert Ruess and Fred J. Schwartz acted as editors. Craig Walsh was Project Manager.

Because of space limitations, the Editors regret that it is impossible to credit by name the numerous individuals in industry, in educational institutions and in government positions and the many firms who supplied background and specific information, criticism and comments and illustrative material. In a few cases where the editors drew extensively on the work of an individual or organization specific credit is given.

Of particular value was the advice and actual material furnished by the following expert consultants: R. P. Lyon, D. K. Bisson, F. E. Gentry, F. W. Gutzwiller, and R. E. Eysell, General Electric Co.; W. H. Ha[illegible]naha, Automatic Production Research; Richard C. Hitchcock, Synthane Company; John H. Miller, Weston Electrical Instrument Corp.; Robert MillIron, Wright Air Development Center; Richard M. Purinton, Consulting Engineer; Frank Rockett, Airpax Products, Inc.; and Milton Tenzer, U. S. Army Signal Engineering Laboratories.

ABSTRACT

The three volumes of this series, of which this is Volume 2, are working manuals for the designer of military electronic equipment. The purpose of these manuals is to provide the engineer with essential data on component parts so that he may select and use these parts in end equipment with the greatest degree of reliability.

Volume 1 discusses the criteria for proper selection of component parts generally, the military specification system, the implications of the use of nonstandard parts and, in the major portion of the book, four basic component parts—resistors, capacitors, relays and switches. Because of space and time limitations, the only types of these basic components covered are those for which a coordinated tri-service military specification exists.

This volume covers power sources and converters including selenium, germanium, and silicon rectifiers, vibrators, dynamotors, transistorized power supplies and batteries; fuses and circuit breakers; electrical indicating instruments; printed wiring boards; solder and fluxes; choppers; blowers; and transmission lines and waveguides. Most of the emphasis is on component types for which military specifications exist, but other types are covered as well.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

George F. Watkins
Lt. Colonel, USAF
Chief, Electronic
Components Laboratory
Directorate of Laboratories

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

INTRODUCTION

The overwhelming need for improved reliability of military electronic equipment brought about the preparation of this technical report. Factual information is presented on component parts needed by the equipment designer to enable him to select the proper component for a particular application and then to use it so that a reliable design is realized.

This is the second of three volumes planned for this report. Volume 1 discussed four components—resistors, capacitors, relays, and switches. This volume gives application information on the following components: power sources and converters, fuses and circuit breakers, electrical indicating instruments, printed wiring boards, solder and fluxes, choppers, blowers, and r-f transmission lines and waveguides. The components planned for coverage in Volume 3 include transformers and inductors, connectors, wire and cable, terminals, tube shields, vibration isolators, gaskets and seals, and hardware.

Military electronic equipment must perform the task for which it is designed, at the required instant during a mission, and under the environmental conditions encountered. In other words, the equipment must be reliable. It must operate without failure for a given period of time.

Military equipment has become complex to a degree which was unbelievable at the close of World War II. In spite of the continual increase in complexity, reliability must not only be maintained, but it must be improved so that new weapons will have the required effectiveness.

The unreliability of much of the present equipment is due not so much to unreliable components but, in many cases, to their improper use in circuits and to improper mechanical and thermal designs.

A mature engineering design, including the proper application of components, must be combined with a capable manufacturing organization equipped to control the quality of materials, processes, and manufacturing operations if the production of reliable military equipment is to be accomplished.

The engineering-manufacturing team must produce a design that can be manufactured using available electronic component parts to perform the required task reliably in the hands of the customer—The Military Departments.

To accomplish this, it is necessary to prove the design and the manufacturing operations by laboratory tests, field tests, and evaluation tests, first, of the engineering model and, second, of the production pilot models. These examinations must be made by technical

and operational people under service conditions, and the necessary corrections must be made before the start of production for actual field use.

It is hoped that the information found in these volumes will materially aid the designer of military electronic equipment in his effort to design and build very reliable equipment and systems for use by our Military Departments.

LEWIS M. CLEMENT

Member, Advisory Group on Reliability of Electronic Equipment, Office of the Assistant Secretary of Defense (Research and Engineering).

Chairman, Electronic Applications Committee (M7), Electronic Industries Association.

Contents

CHAPTER 1 POWER SOURCES AND CONVERTERS

Chapter 1

POWER SOURCES AND CONVERTERS

All electronic equipment requires electrical power, and over the years every practical means of securing this power has been utilized, including hand-cranked electric generators. Today, most military electronic equipment is powered from conventional sources of a-c power at various voltages and frequencies; but much is also powered from batteries either directly, as is the case with portable equipment, or through such devices as the dynamotor or vibrator. These several sources of power are treated in this chapter.

RECTIFIERS—SELENIUM, GERMANIUM, AND SILICON

It is a rare situation when a-c power obtainable from prime movers or from public utilities can be used without alteration in electronic equipment. Usually the voltage must be lowered or raised, and in virtually every case considerable d-c power is also necessary.

Most electronic equipment gets its required direct current from tube rectifiers, but an increasing amount of equipment utilizes semiconductor rectifiers. The shift from tube rectifiers toward semiconductor types is very evident. Tubes as component parts of power supply systems and the systems themselves are adequately covered in existing literature and are not considered here. Instead, semiconductor rectifiers are treated in some detail to aid the design engineer in selecting and using them to attain the greatest degree of reliability.

Semiconductor Rectifiers

At the present time, such semiconductor materials as selenium, copper oxide, copper sulfide, germanium, and silicon are widely employed as rectifying elements. Each of these materials has advantages and disadvantages.

Most widely employed in military equipment are rectifiers using selenium, but coming in much wider use are rectifiers made from silicon and germanium.

Current and Voltage Ranges

Figure 1-1 shows the wide range of voltages and currents being supplied by semiconductor rectifiers. Thus, the range is from a high-voltage low-current dust precipitator (50,000 volts at 0.15 amp) to a low-voltage high-current power source for a synchrocyclotron requiring 20,000 amp at 21 volts. It is understood, that this range is typical only and not limiting.

Definitions

As in all other technical matters, manufacturers and users of semiconductor rectifiers have created their own terminology, often using words which have different meanings in other branches of technology. A few of the generally used terms are defined below.

Forward Direction. The direction of least resistance to current flow through a rectifying element or cell.

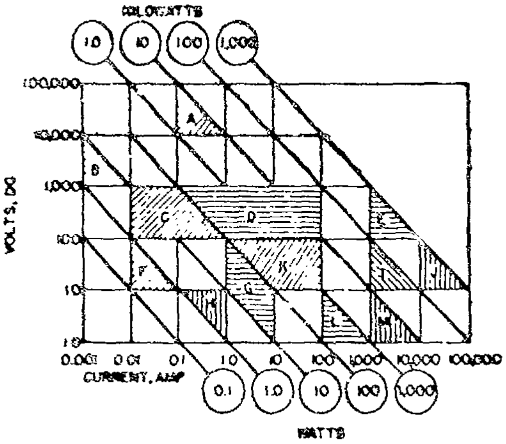


Fig. 1-1. Typical applications of d-c power which can be supplied by semiconductor rectifiers. (A) Industrial dust precipitator, (B) Home-type dust precipitator, (C) Electronic, television, radio, audio amplifiers, etc., (D) Motor control, variable speed, dynamic braking, etc., (E) Power conversion, (F) Magnetic amplifiers, (G) Automotive-battery chargers, (H) Trickle chargers, (I) Arc furnace, (J) Cyclotron magnet, (K) Telephones, industrial trucks, business machines, aircraft, (L) Cathodic protection, (M) Electroplating.

Forward Current. Forward current is the current flow in the forward or conducting direction.

Forward Voltage Drop. The voltage drop that results from the flow of current through a rectifier in the forward direction.

Applied Voltage Rating. The maximum recommended a-c voltage that may be applied to a rectifier.

Reverse Direction. The direction of greatest resistance to current flow through a rectifying cell.

Back or Leakage Current. Current that flows in the reverse direction when the applied voltage is on the nonconducting half cycle.

Back Voltage. Voltage drop across rectifier when applied voltage is in the nonconducting or reverse direction.

Peak Inverse Voltage Rating. The maximum potential that may be impressed across a rectifier under specified conditions.

Base Plate. Metallic plate on which rectifying material is coated. Usually aluminum, nickel plated, for selenium cells.

Blocking Layer. Very thin layer between selenium and counterelectrode. Also called the "junction" or barrier layer.

Cell. Basic rectifier consisting of a positive electrode, a negative electrode, and a rectifying junction. A single cell is a rectifier; rectifier stacks are sometimes made up of several cells.

Counterelectrode. A good conductor separated from the selenium layer by the barrier or blocking layer, sometimes called the alloy.

Stack. An assembly of cells into a completed practical rectifier.

Cartridge Stack. A number of cells in series, mounted in a unit for small-current, high-voltage applications.

Power Stack. A rectifier having long life on high-current, medium-voltage heavy duty. For welding and general shop use.

Tube vs. Semiconductor Rectifiers

Both types of rectifiers have advantages and disadvantages. Gas-filled hot cathode rectifier tubes may be about as efficient as semiconductor rectifiers except at low voltages, but most electronic equipment utilizes high-vacuum rectifiers, which are not so efficient.

The greater efficiency of the silicon or germanium power rectifiers compared to vacuum tube rectifiers has a very important bearing in military equipment where reduction in weight is always welcome.

A useful study by Perlman of Rome Air Development Center, U. S. Air Force, gives a direct comparison of two rectifier systems employing the same components except that one used a 5U4G tube and the other a silicon power rectifier. Table 1-1 gives the data.[*]

The lower internal resistance drop in the silicon rectifier shows up in the decreased input voltage required to deliver the required output voltage (250) and current (500 ma). This means that 14 percent fewer turns would be needed on the secondary of the input power transformer. Furthermore, no filament winding would be needed. By redesigning the power transformer and filter chokes, utilizing larger wire with less voltage drop, still further

[*] Perlman, Sol, "The Power Supply in Military Equipment," IRE Convention Record, Part 8, 1958.

Table 1-1—Rectifier Comparison, Tube vs. Silicon

Property	Vacuum tube	Silicon	Silicon
	With original power transformer and chokes		With redesigned transformer and chokes
Input power, watts	229	163	141
Anode voltage to rectifier, volts ac	391	226	240
Efficiency of power utilization, %	56	74.4	88.6
Power dissipated in power supply, watts	98	42	18

economies in waste heat could be secured. Because the transformer and chokes would be no larger than those of the tube power supply system and because the silicon unit would be smaller than the 5U4G tube, better placement of these components within the equipment could be secured. Where the tube rectifier might have a bulb temperature rise of 150 C above ambient, a properly mounted silicon unit would probably experience a heat rise above ambient of only 5 to 10 C.

Morison also points out the fact that a single power transistor "can effectively perform as well as ten series regulator tubes (type 6080W) with about one-fifteenth of the power loss."

Therefore, the designer of new equipment should entertain seriously the possibilities of using silicon or germanium rectifiers for the power supply system and Zener diodes or power transistors as regulators where the power supply voltage must be regulated.

It is worth noting that a typical GCA equipment mounted in a trailer employs eight tube-regulated power supplies, that a 7-1/2-ton ice-capacity air conditioning unit is required for equipment cooling, and that the radar equipment and air conditioner each require a gasoline-engine driven generator for its operation. It is easy to visualize the savings in complexity, heat dissipation, and weight by proper usage of semiconductor devices instead of conventional tube equipment in such power supply systems.

GERMANIUM AND SILICON RECTIFIERS

In less than a decade, new semiconductor rectifiers made from silicon and germanium have become major competitors of the older selenium, copper oxide, and magnesium copper sulfide types. These new rectifiers resulted from wartime work on crystal diodes. Since the development of the large-area germanium rectifier cells in 1952, over 20,000 kw for d-c power use have been installed.*

Well-designed germanium and silicon rectifiers that are well made can provide the following features:

1. High efficiency. At rated current, the forward voltage drop of germanium units may be less than 0.7 volt and less than 1 volt for silicon. Thus, the voltage and power lost in the rectifier itself is very low. (See Fig. 1-2.)

2. High reverse resistance. Over the rated temperature range for each type, the resistance in the nonconducting direction is so high that the leakage current is negligible.

3. Stability. The forward and reverse characteristics of a well-made silicon or germanium junction do not change with time. Hermetic sealing precludes deterioration of the reverse characteristics due to leakage paths around the junction caused by moisture or contamination. The junction is formed during the initial fabrication process. No additional junction formation is required when the rectifier is put into service.

4. Corrosion resistance. With the junction sealed in a hermetic package, it is the package and not the junction which determines the ability of the rectifier to withstand corrosive atmospheres and fluids.

5. Wide temperature range. Proper design permits germanium units to be operated from -65 to 105 C and silicon from -65 to 200 C. JAN and Navy specifications are for a maximum temperature of 75 C for low-signal

* Wahl, R. E. "Direct Water Cooled Germanium Power Rectifier," Communication and Electronics, AIEE, January 1957.

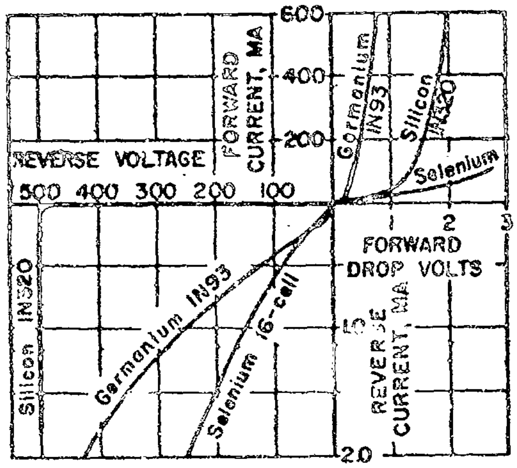


Fig. 1-2. Comparison of selenium, germanium, and silicon rectifier characteristics.

germanium and 55 C for higher power (N93), and manufacturers producing to military specifications will not specify above 150 C ambient.

6. Small size. The only limitation on compactness is the ability to dissipate the heat generated internally. Because of the low forward-voltage drop and small leakage current, little power must be dissipated by the rectifier and, therefore, the rectifier package can be small. "Some of the tranformerless units (water-cooled) have almost 10-kw output per cubic foot of volume required and up to 60 kw per square foot of floor space required." *

All of these advantages cannot be attained without some minor concomitant drawbacks. Germanium and silicon rectifiers are not selfhealing when they are subjected to voltages in excess of their breakdown voltages in the way that selenium rectifiers sometimes are. Overload currents must be considered with more care in germanium and silicon cells because their low effective internal resistance does not limit the circuit current, and their high current density results in concentrated heating. Selenium rectifiers find some measure of self-protection in current limiting by their higher cell resistance and from less concentration of heat due to their lower current densities.

At present, single silicon cells can be supplied for maximum current ratings only as high as about 60 amp average. On the other hand, silicon can handle considerably higher peak inverse voltages compared to germanium so that fewer units in series will be required. For voltages above about 100 (dc) where two or more germanium units in series would be required, the use of a silicon rectifier seems indicated. Typical characteristics for silicon, germanium and selenium rectifiers are listed in Table 1-2.

Silicon seems to have better peak inverse voltage characteristics with respect to temperature than germanium whose leakage increases and peak inverse voltage decreases as the rectifying junction temperature increases.* The same effects occur with silicon but at higher temperatures.

Although as stated above the whole situation regarding these newer types of rectifiers is extremely fluid, the following statements can summarize the picture as of February 1958. Table 1-2 gives additional data but is subject to wide changes with time.

Selenium. Attractive from the standpoint of long experience, wide power range, low cost, good reliability, and overload protection.

Germanium. Highest in forward efficiency but not suitable for high-temperature operation.

Silicon. Has definite overload limitations but has the highest operating temperature capabilities and the lowest leakage; expensive.

There is no simple clear-cut answer to the question "which type of semiconductor rectifier shall be used?" Each type has certain outstanding characteristics; and where these characteristics are significant in an application, they form a basis for a logical selection.

In summary, however, selenium rectifiers offer good service under conditions where overloads of voltage and current are frequently encountered. Silicon rectifiers offer high-temperature operation and very low reverse currents. Germanium rectifiers offer very low forward voltage drops and excellent regulation.

Although the fundamental principle of operation is the same whether the semiconductor

* Wahl, R. E., "Direct Water Cooled Germanium Power Rectifier," Communication and Electronics, AIEE, January 1957.

Table 1-2—Comparison of Half-Wave Semiconductor Rectifiers*

Property	Selenium	Germanium	Silicon
Working current density forward, amp per sq in.	0.10	600	600-630
Overload, current density, forward, amp per sq in.	up to 20 times (see duty cycle)	10 times	5 times
Working forward drop of cell, volts	0.7-1.5	0.6-0.65	1.25
Initial forward drop (I-0), volts	0.3	0.2-0.35	0.4-0.7
Reverse current density, amp per sq in.	0.01	0.15	0.15
Reverse voltage per cell, rms	15-45	3.5-400	3.5-1000
Reverse voltage per cell, peak	21-64	5-1500	5-1500
Overload (reverse) voltage, % below MPIV	40	20	20
Frequency, max	400-1000	20,000 50 Mc (thin)	20,000 50 Mc (thin)
Capacitance per sq in, mmf	20,000 old 2000 new 100 future	—	—
Max ambient temperature, deg C†	150	65	200
Max hotspot temperature, deg C	170	100	210
Heat sink required ‡	No	Yes	Yes
Efficiency, %	80	99	99
Largest size, in.—forced air rating, amp	12 × 16; 72	600	600
Smallest size, ma	5 (Syntron)	1.5	1.5
Resistance to contamination	Thick paint and hermetic seal	Hermetic seal	Hermetic seal

* From R. C. Hitchcock and S. E. Brayshaw, Syntron Company.

† Two types of selenium: standard for 45 C ambient and 90 C hotspot; high-temperature units for 125 C.

‡ Selenium is an area-type rectifier with a built-in heat sink.

is germanium, selenium, or silicon, the methods of construction and operating characteristics differ in various ways. For that reason each type is treated separately in what follows.

SELENIUM RECTIFIERS

Aside from instrument rectifiers, which employ copper oxide, selenium units are the most widely used of all the semiconductor types in the electronic industry at the present time. There are two basic forms of this rectifier. One is the enclosed cartridge style, consisting of a number of disk cells in intimate contact, which is frequently used in low-power circuits. The other is the stack form commonly used in medium- and high-power circuits.

Construction Details

The construction details of a typical selenium cell are shown in Fig. 1-3.

Cell Elements. Listed below are the parts of a single selenium rectifier cell. The manufacturing processes described are basic, each manufacturer's processes varying.

Base Plate. The base plate is aluminum from 0.10 to 0.40 inch thick, and is either nickel or bismuth plated. Often it is etched. When expense is not important, a solid nickel base plate may be used; but when economy is important, an iron plate may be clad with aluminum and then nickel plated. The nickel is essential to make the selenium adhere to the base plate.

Selenium Application. Actual methods for applying the selenium are each manufacturer's secret, but in general the material may be evaporated onto the base plate, pressed on it from a powder at 2000 psi at 125 C, or applied in a molten layer. By controlled heat treatment, this selenium layer is converted to the required crystalline structure.

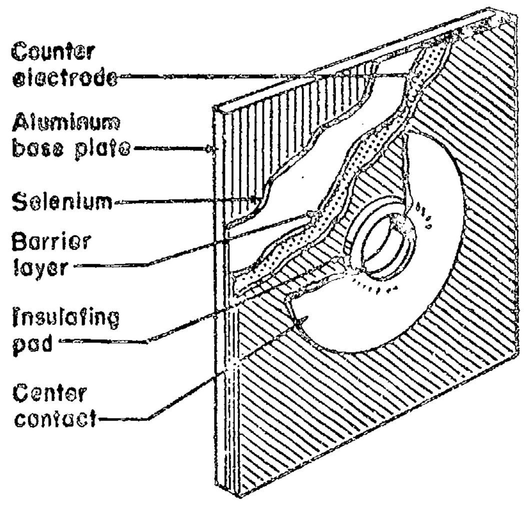


Fig. 1-3. Basic details of a selenium cell.

Blocking Layer. The methods by which the blocking layer is applied or the material from which it is made are secret. A poor blocking layer is a major defect in an otherwise good rectifier and is the chief contributor in cell aging.

Counterelectrode. This is a layer of cadmium-bismuth or cadmium-tin, sprayed onto the selenium surface.

Stacks. Individual selenium rectifier cells are grouped in stacks, which include three broad classifications by use: cartridge, radio, and power. There will be cases where the line of demarcation is not clear-cut, but in general: cartridge stacks are groups of cells in series for high voltages and low currents, 600 volts and up, 50 ma and down. Radio stacks are groups of cells in series for medium voltages and currents, 150 to 400 volts, 50 to 500 ma. Power stacks are single, series, or series-parallel cells for medium and low voltages and heavy currents; 3 to 30 volts and hundreds of amperes for electroplating, 30 to 60 volts and 100 to 500 amp for welding, 125 to 460 volts and 100 to 1500 amp for applications where power of this magnitude is required.

Cartridge Stack. Round cells can be stacked in series, all facing the same way and in intimate contact. (See Fig. 1-4.) A metal slug at the alloy (positive) end, and a helical spring at the base metal (negative) end, are pushed together to make a tight spring-loaded assembly. Glass-to-metal sealing compound provides a hermetic seal. (See Fig. 1-4.) The slug and spring are dimensioned so that the cells are outside the edges of the ferrule connections.

The thickness of the rectifier disks varies with the manufacturer, from 0.010 to 0.040 inch thick base plate, plus about 0.008 inch of selenium and alloy, so that the active stack length ranges from

$$\text{volts per inch} = E_r/0.018 = 55.5\,E_r \text{ to}$$

$$\text{volts per inch} = E_r/0.048 = 20.8\,E_r$$

where E_r is the inverse reverse voltage rating of each cell. Actual working length depends on both the voltage of the cells and the number of cells.

In general, the active length

$$L = (\text{volts required})/(\text{volts per inch})$$

Therefore, for a 5000-volt stack with 125 cells, each with E_r equals 40 volts, the two extremes of active length are

$$0.018 \times 5000/40 = 2.25 \text{ inch,}$$
$$\text{and } 0.048 \times 5000/40 = 6.00 \text{ inch.}$$

Radio and Power Stacks (Open Construction). In general, the construction of a typical stack is as follows: The individual cells are assembled on a metal mounting stud insulated by a length of phenolic tubing. A small insulating washer is placed against the alloy side of the cell. A larger spring-contact washer is then placed over the insulation (pressure-limiting) washer and against the alloy side of the cell. Each individual cell is separated by

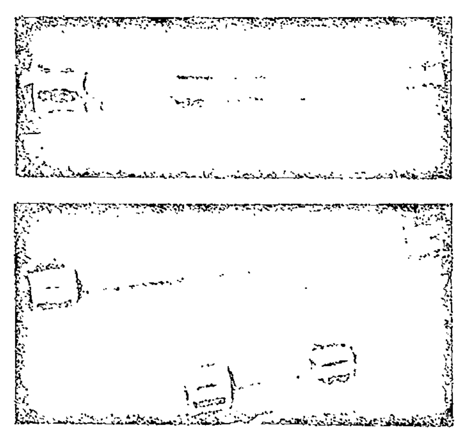


Fig. 1-4. Exploded view (top) of selenium cartridge-type rectifier stack. Assembled view (bottom) of selenium cartridge-type rectifiers.

either metal or insulating spacer washers, depending upon whether or not direct connection between cells is required. The a-c and d-c terminals are then placed in their proper positions on the assembly. Finally, insulation washers are added at the ends, and the entire assembly is secured with lock-washers and nuts. The polarity of a rectifier may be determined by inspecting the stack; the side of the cell with the spring washer is always positive, and the plated side is negative.*

Power stacks are characterized by heavy currents which require large plates or cells. Figure 1-5 shows a stack of 6- by 10-inch cells with two mounting studs. Figure 1-5, also shows a stack of 12- by 16-inch cells with six studs. The construction is the same as in Fig. 1-6, except that the tubing, washers, and so on, are duplicated for each stud.

Spring and Contact Washers. Figure 1-7 shows some typical contact arrangements. A selenium rectifier operates satisfactorily when there is a definite amount of intercell pressure; too little is bad for the forward drop, and too much crushes the selenium crystalline surface and ruins the reverse voltage characteristics.

Spring Washer and Insulating Spacer. Figure 1-7(A) is a good arrangement, used by the stack of Fig. 1-6, where IW is the insulating washer which restricts the maximum motion of the spring washer SCW. Therefore, axial force exerted by the mounting bolt will squeeze the contact washer tight against the insulating washer, but not against the working area (WA) of the selenium.

Sinuated Spring Contact. In Fig. 1-7(B) a sinuated spring member makes multiple contacts on a working area of alloy and selenium. An advantage of this type is the free flow of air through the curved spring member. It is not easy to provide definite spring pressure, or a low-resistance contact with Fig. 1-7(B). This type of contact is mainly used for radio stacks of relatively low current.

Solid Contact Washer. This contact uses a solid contact washer CW, as shown in Fig. 1-7(C). A thin insulating washer IW is placed on the selenium layer before being sprayed with alloy. This insulating washer is slightly larger in outside diameter than the contact washer. When the solid contact washer CW

* ADN-11050, 10 June 1958.

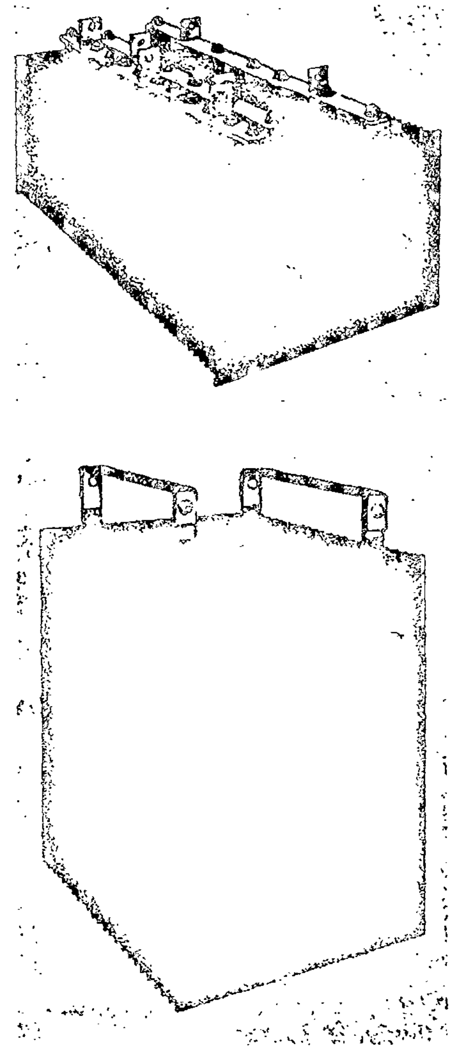


Fig. 1-5. Power stack (top), three-phase full-wave bridge, 6- by 10-inch cells. Power stack (bottom), half-wave 12- by 16-inch cells.

is squeezed firmly, it cannot damage the working area of the selenium WA.

Solid Contact Disk. This type is shown on Fig. 1-7(D) where the working area is in the center of the cell. A thin insulating washer has a central hole around the working area, and the counterelectrode is placed over both the insulating washer and working area. The diagram is exaggerated for clarity. Stacks of these disks can be pressed firmly together without crushing the selenium in the active area. The scheme of Fig. 1-7(D) is expensive, and for low-current applications it is not often justified. The construction of Fig. 1-4,

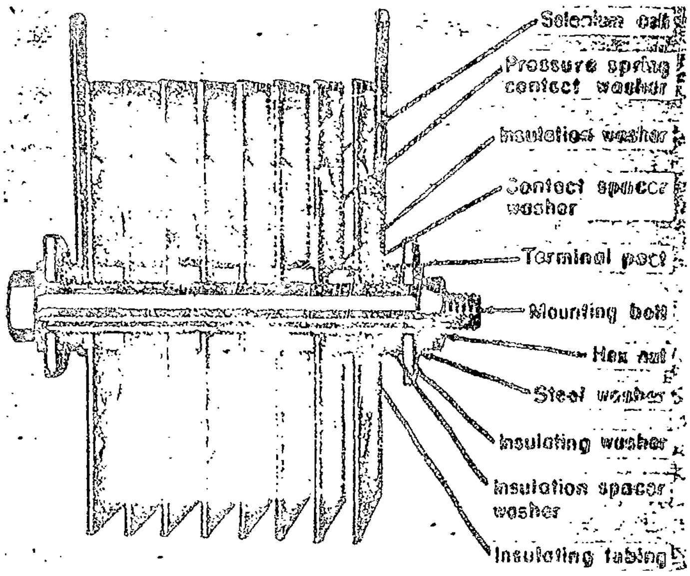


Fig. 1-6. Cross-section view of a radio-type rectifier stack.

with a single contact spring at one end, is adequate for disks up to 0.500-inch diameter, in which the whole surface is the active area.

Cross Connectors. On Fig. 1-5 the terminals are copper straps rising from the central spring washers. At the top, the common terminals are joined by a cross connector, so that they are paralleled. Figure 1-5 has a three-phase input, the left-hand edge showing three sets of input terminals. The d-c output has two terminals, each with a spare terminal parallel connection.

Figure 1-5 shows a half-wave stack with two terminals. the front of Fig. 1-5, the short left bus is connected to the longer right-hand terminal by a short, welded cross connector.

Preventing Cells From Turning. When a cell has two or more round holes, there is no problem of turning. See Fig. 1-8(C). The mounting bracket is securely held by the studs, with the construction around each stud as shown in Fig. 1-3.

Square Hole. On Fig. 1-8(A) a square hole in each cell is filled with a square insulating tube which prevents turning. Obviously any shape which is not circular can replace the square shape.

Edge Holes. Figure 1-8(B) shows a cell with semicircular holes to fit insulating rods, which in turn are held securely by the end plates.

Straight-Line Construction. It is often convenient both from an assembly standpoint and from a usage standpoint to have a rectifier stack made in a single straight line. In Figs. 1-48 and 1-49, all rectifiers are shown schematically in a straight line with external connection points indicated by small circles. Appropriate insulating washers are provided to keep the circuits electrically separate. For example, the three-phase full-wave bridge "Z" of Fig. 1-52 may be duplicated electrically by using six half-wave stacks "R" of Fig. 1-48, or three single-phase doubler stacks such as those used in Fig. 1-49. In general, the added space is not available for separate rectifier stacks, and the straight-line single-unit construction is preferred. However, the designer should bear in mind that it is not good practice to combine in a single stack rectifiers furnishing power to separate electrical circuits and that the maximum stack length must be consistent with shock and vibration requirements imposed by military service.

Terminals. Any desired type of terminal may be supplied. Small cartridge stacks often have fuse-clip connectors, or pigtail leads. Radio stacks have solder-type or plug-in banana terminals. Power stacks usually have bolt-on connections.

Brackets. Mounting brackets are used on a variety of applications. A right-angled piece of steel is bolted to the rectifier studs and to the apparatus using the rectifier. On large cell stacks, the bracket serves a dual pur-

pose. It holds the rectifier in place and it protects the plates from physical damage.

Shock-mounted brackets are a special case. For some applications of severe vibration, or expected shock, the brackets are intentionally made resilient to minimize the shock transmitted to the rectifier stack.

Encapsulation. In some instances a solid insulating material surrounds the rectifier stack; the terminals emerge to make electrical connections. The purpose is to retard or prevent the penetration of moisture to the cells. The insulating material is usually a thermosetting plastic, which sets below 80 C, since higher temperatures may damage the cells. Encapsulated rectifiers are not as readily cooled as those which may be directly cooled by convection or forced air, and are often derated on allowable load currents. For high-voltage cartridge stacks, a vacuum and pressure tight joint of terminal caps and surrounding insulating tube is regarded as a hermetic seal.

Paint and Varnish. After assembly and test, a selenium rectifier is usually painted. First the terminals are masked off and then the paint is applied by dipping or spraying. The ideal coating is somewhat flexible, opaque, and strongly adherent. In addition, it must be compatible with the rectifier. The goal is a coating which resists normal atmospheric conditions of dust, moisture, salt, atmosphere, and fungus growth. The paint may be air dried or baked dry. The exact formulation varies with each manufacturer.

Salt-Spray Finish. To successfully resist salt spray, a thick coating is needed. Usually this is a multiple coating. If it is baked it must be at a temperature consistent with the selenium cell characteristics.

Fungicide Finish. A fungicide varnish may be applied after all other paint coats. As a rule, the fungicide finish is applied while the terminals are masked. After the bus bars are connected permanently, it is good practice to spray them with the fungicide finish. Fungicide finish is recommended for tropical or extra high humidity applications.

Final Test. Following all paint applications, the stack is given a final test.

Voltage Test to Ground. The studs (or bolts) and mounting brackets are tested by 60-cycle a-c equipment, usually with twice the rated

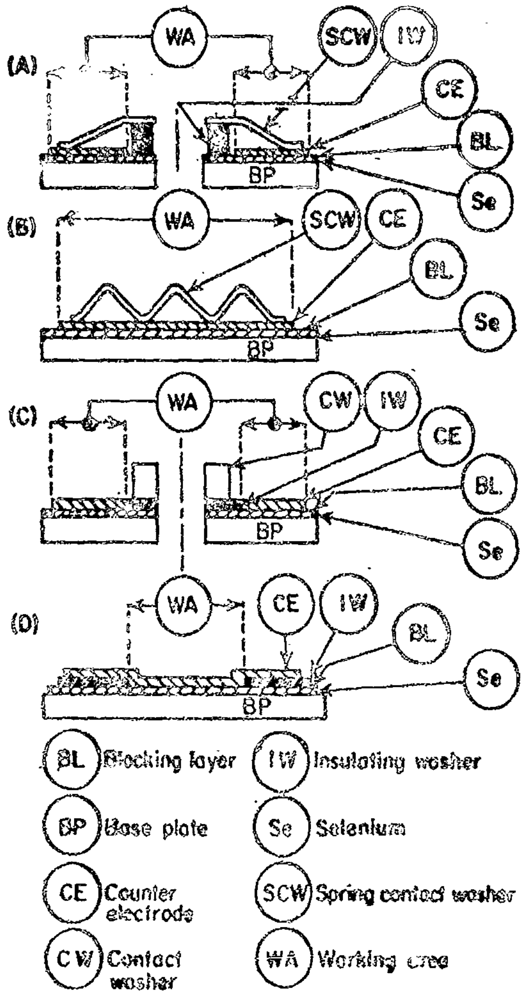


Fig. 1-7. Typical contact spring arrangements for stacking. (A) Spring washer and insulating spacer. (B) Sinuated spring contact. (C) Solid contact spacer. (D) Solid control disk.

voltage plus 1000 volts to each terminal. There should be no breakdown.

Operation Test. Typically this is in two parts for a single-phase bridge: first the a-c voltage drop, with the d-c terminals short circuited, is measured; then the reverse a-c current at rated a-c voltage, with the d-c terminals open circuited, is measured. Test details and requirements of the military specifications are given later in this chapter.

Cell Formation. During this process the blocking layer is formed, that is, its resistance in the reverse direction is increased. Before forming a cell may refuse to pass appreciable current with up to 10 volts applied;

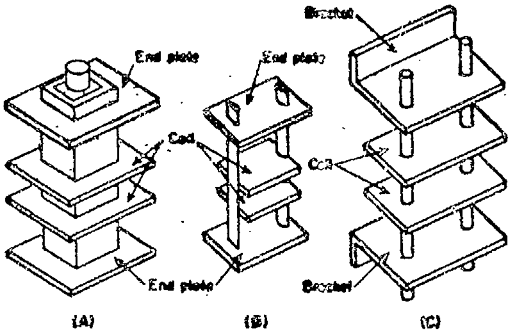


Fig. 1-8. Methods used to prevent cell rotation. (A) Single nonround hole. (B) Edge holes. (C) Two-hole assembly.

but, after forming, the blocking voltage may be as high as 45 volts. The actual forming process consists in forcing current through the cell in the reverse direction according to a definite time schedule.

Cell Tests. After forming, the cells are tested and may be rated in groups. Figure 1-9 gives typical current densities for two types of service, convection cooling, and forced-air cooling.

Convection Cooling. For this service, the cells are tested with a forward current of 0.700 amp per sq in. where the forward voltage drops are as shown in the table below.

Rectifier grade	Forward voltage drop* (volts)
A	0.9 - 1.20
B	1.21 - 1.40
C	1.41 - 1.60

Forced-Air Cooling. For this service, the cells are tested with a forward current of 2.35 amp per sq in. where the forward voltages are as shown in the table below.

Rectifier grade	Forward voltage drop* (volts)
D	1.50 - 1.70
E	1.71 - 1.90
F	1.91 - 2.10
G	2.11 - 2.30
H	2.31 - 2.50
J	2.51 - 2.70

*Rating and testing used by Syntron Company.

For convection applications, the curves for A, B, and C cells are not generally applicable above 0.700 amp per sq in. because of random variations in cell characteristics. That is, an A cell does not necessarily follow the area between curves I and II of Fig. 1-9 at current densities higher than 0.700 amp per sq in. However, because the test for D through J is severe, it is permissible to use a D or an E cell for convection-cooled conditions as an A cell at current densities of 0.700 amp per sq in. Similarly, F and G forced-air ratings can be used as B convection ratings, and H and J for C convection ratings.

Figure 1-10 shows the rms forward voltage drop as a function of load current factor for six typical B-rating selenium-cell circuits. Examples: A single-phase bridge for capacitor or battery loads, curve 1, at normal load, will have a rms forward drop of 1.92 volts. For a single-phase bridge resistance load, curve 4, at normal load, will have a rms forward drop of 1.18 volts.

High-Density Cells. At present there is no agreement on what constitutes a "high-density" forward current for a selenium cell for convection-cooled applications. One suggested high density is 0.600 amp per sq in. for bridge-circuit resistance loads, and 0.500 amp per sq in. for a bridge circuit with capacitor loads.

The real question is not that of forward current density but of the operating temperature. A high density cell will run hotter than a standard density cell, with shorter expected life.

NEMA standards for metallic rectifiers, MRI-1953, states that the normal current density of a single self-cooled selenium cell, operating at an ambient temperature of 35 C, shall be approximately 0.25 rms amp (0.16 amp dc) for each square inch of rectifying area. The actual current density at which a particular rectifier cell is rated depends upon the quality of the product and the manufacturer's interpretation of normal life expectancy.. For military applications, where the design ambient temperatures normally exceed 50 C and where high reliability and long life are important considerations, convection cooled cell current densities at which the rectifiers are used are normally much lower than the 35 to 40 C basic rating, which the rectifier manufacturer assigns to his cells.

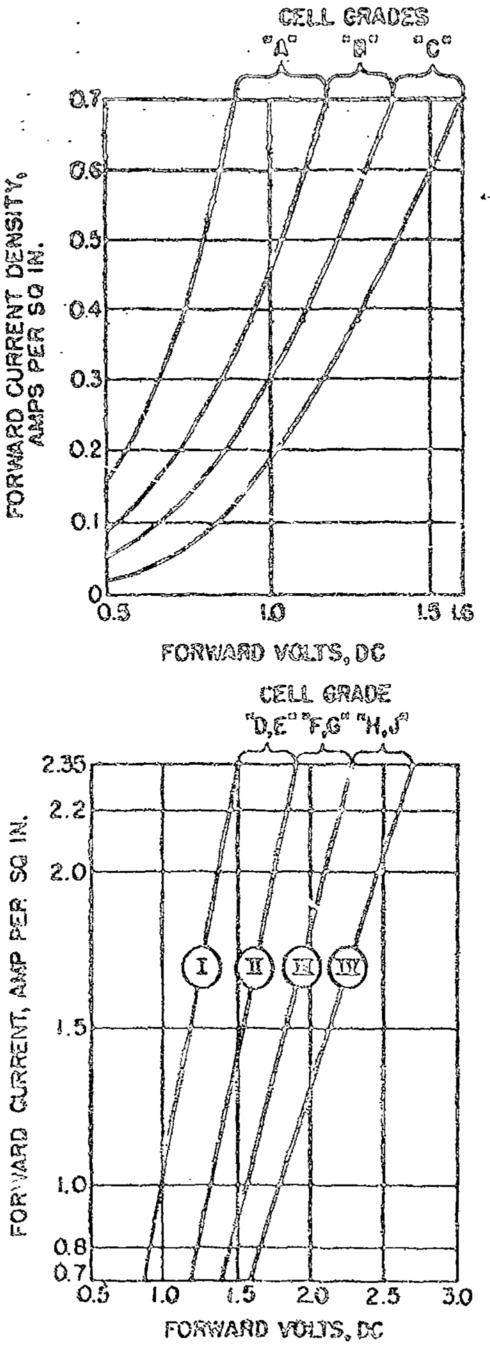


Fig. 1-9. Selenium cell grades (top), convection cooled. Selenium cell grades (bottom), forced-air cooled.

Standard Voltages

The voltage rating of a particular rectifier depends upon that of the individual plates and whether the plates are put together in series or parallel. Early selenium plates were limited to input voltage ratings of 14 to 18 volts rms, but more modern techniques have made possible a standardized series of higher ratings, notably of 26, 33, 36, 40 and 45 volts.

The use of 45-volt plates may result in substantial reduction in the size and weight of a stack. For example, in applications requiring 30- to 33-volt d-c output into a resistive or inductive load, an 8-plate, single-phase, bridge-rectifier stack is needed if 26-volt plates are used. With 45-volt plates, the assembly can be reduced to 4 plates, giving a space and weight reduction of about 50 percent. Depending upon applications, similar reductions are possible with 33-, 36-, and 40-volt plates. The need for 12-volt battery chargers dictated by the advent of 12-volt ignition systems in automobiles is a case in point. The most economical circuit for this application is a center-tapped bridge, for which a pair of 26-volt plates per arm are normally required. The rectifier assembly can, however, be reduced to about half size by using a single 33-volt plate per arm.

SELENIUM RECTIFIER OPERATING CHARACTERISTICS

Operating characteristics differ with methods of manufacture, age, temperature, and other variables. All, however, display the typical steep current rise with voltage in the forward direction, and the relatively flat current curve with voltage in the reverse direction. Note that in Fig. 1-11, 20 volts in the reverse direction produces a current through the rectifier of only 0.004 amp per sq in. of surface, while only 1 volt in the forward

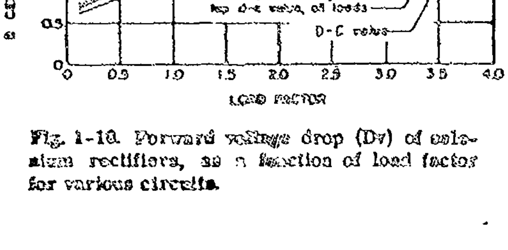


Fig. 1-10. Forward voltage drop (Dv) of selenium rectifiers, as a function of load factor for various circuits.

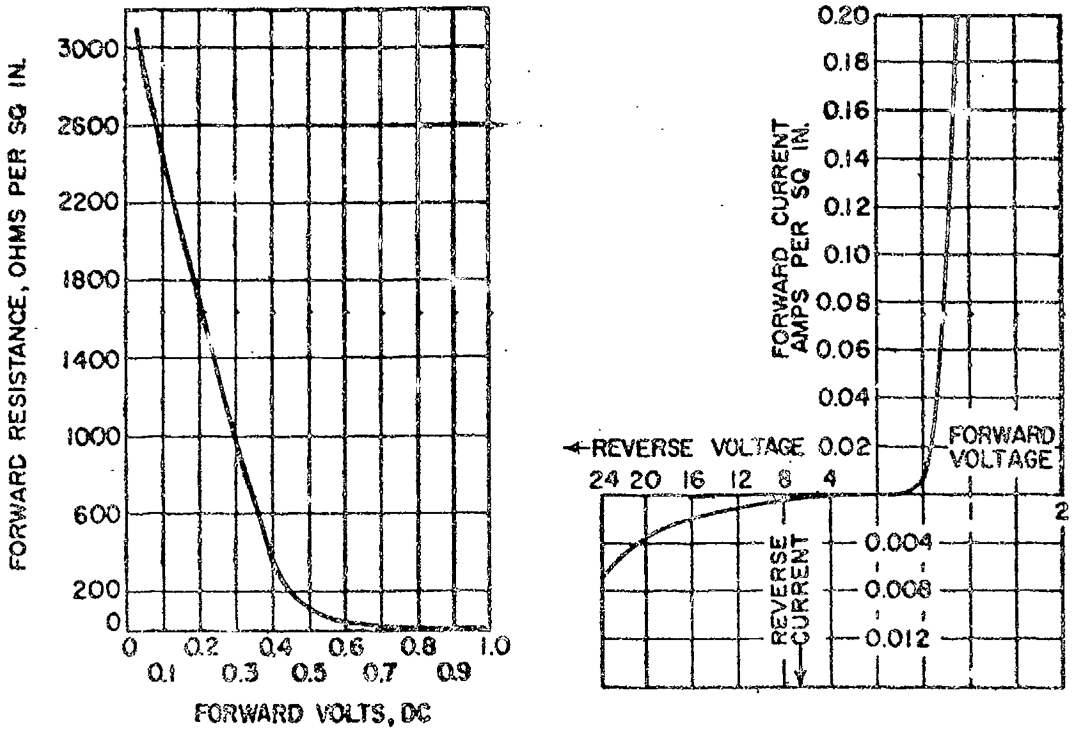


Fig. 1-11. Curves for a typical selenium rectifier, forward voltage vs. forward resistance (left), and volt-ampere characteristic (right).

direction permits over 0.2 amp per sq in. to pass.

Direct Current Obtainable

The current passed by a selenium rectifier is a function of the voltage and the area of the rectifying surface. Figure 1-12 shows the approximately straight-line relation with radio stacks on log-log scales of current as a function of area for a given voltage. Although only two standard voltages, 26 and 45, are shown for two circuit configurations, single-phase and six-phase star, the range of currents that can be handled is clear. In Fig. 1-13, typical forward current densities for resistive loads are given as a function of reverse voltage and the number of cells in the stack.

Figure 1-14 gives a comparison of the current obtainable from several circuits, all using the same cell.

Life Expectancy

The operating life that can be obtained is mainly a function of the temperature at which the rectifier operates. Moisture vapor and light on the junction are also factors that govern the useful life. End of useful life is that point where the alternating voltage required to produce rated output current and voltage exceeds the value specified for a fully aged cell. A typical relation between ambient temperature and life is shown in Fig. 1-15(A). For this particular case, the manufacturer states that a life span of 80,000 hours can be expected at 35 C, but only 1500 hours at 130 C, although manufacturers can supply units for operation up to 150 C. Low-temperature cells are limited to the operating conditions to the right of the dotted curve in Fig. 1-15(A). In this case, life is defined as a 100 percent increase in forward voltage drop from its initial value.

Although a temperature high enough to melt the counterelectrode causes sure failure, lower temperatures than this can definitely be detrimental to rectifier life. Figure 1-15 (B) shows the temperature rise above a 40 C ambient, from 10 to 100 percent of the full load, to be 38 C. If the temperature is high enough to affect the barrier layer adversely, but not high enough to melt the counterelectrode, rupture of the barrier layer occurs and a reduction of rectification ca-

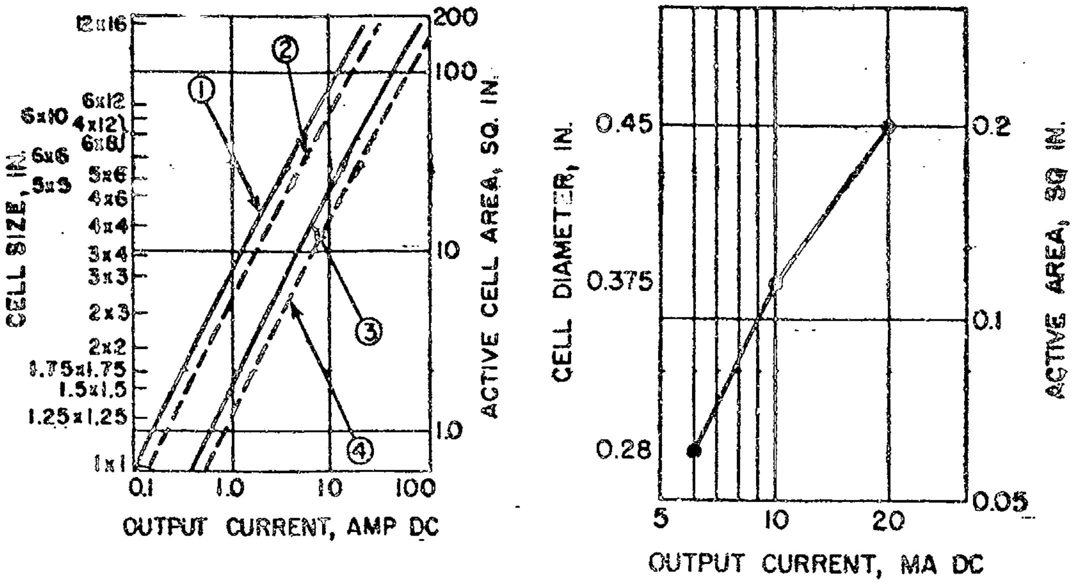


Fig. 1-12. (Left) Permissible current as a function of area, resistive, or inductive load, 40 C ambient, convection-cooled radio and power selenium stacks with 1-8 cells: 1. 45-volt cells, single-phase, half-wave. 2. 26-volt cells, single-phase, half-wave. 3. 45-volt cells, three-phase, full-wave center-tapped. 4. 26-volt cells, three-phase, full-wave center-tapped. (Right) Permissible current as a function of area, resistive, or inductive load, 40 C ambient, convection-cooled cartridge stack.

pacity results. At this point it is likely that an open circuit will occur in the barrier, but the remainder of the rectifying area continues to function. Partial or complete failure generally occurs when the cell temperature is in the region of 100 to 160 C, depending on manufacturing techniques. Rupture of the barrier layer may be caused by hot spots, which in themselves may or may not cause melting of the counter electrode.

The actual temperature rise above ambient is caused by the I^2R losses within the rectifier plus heat absorbed, generally by radiation from surrounding components with higher temperature. Characteristically the I^2R losses increase with time. Because the reverse current occasionally decreases with time for several hundred hours before it starts to increase, there may be an interval in which the total I^2R losses decrease.

An important fact not to be overlooked is that the effectiveness of forced air cooling is limited by the temperature of the air used for cooling. As the temperature of the cooling air rises, it can accept less and less heat from the rectifier. What is important is that the temperature of the barrier layer inside the cell be kept within safe limits. The temperature on the surface of the cell will be less than the temperature at the barrier layer due to the thermal impedance of the materials of the cell.

High-temperature operation is a prime cause of failure because of damage to the barrier layer.

As shown in Fig. 1-15(C), (D), and (E), the operating characteristics of selenium

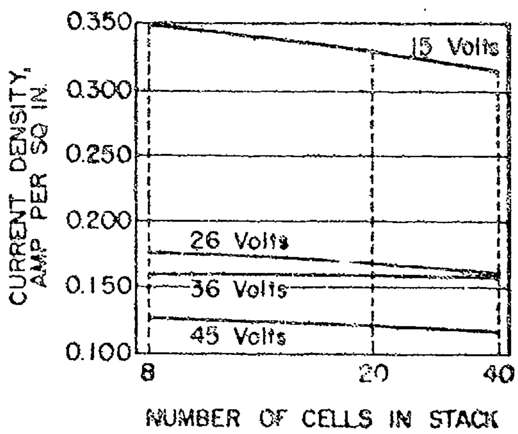


Fig. 1-13. Forward current densities of half-wave selenium rectifiers, resistive load, as a function of stack size and reverse voltage.

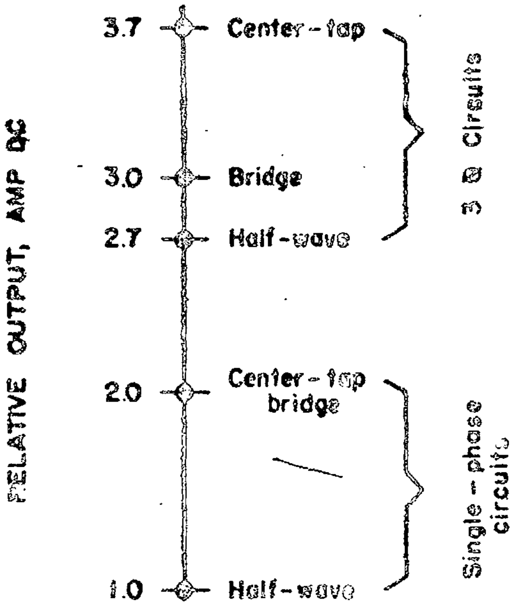


Fig. 1-14. Relative output of various rectifier circuits, all using the same size cell. The figures are based on a single-phase, half-wave circuit having a relative output of 1.0.

rectifiers will vary over long periods even under relatively good operating conditions. These curves show progressively greater deviation from the initial characteristics as the load is increased beyond rated load due to temperature rise. Note that, at twice rated load, the performance is marginal, while at three times rated load, rectifier performance is poor and shortlived. Therefore, not only are the operating characteristics degraded by excessive loads, but the effective operating life is also affected. Note, however,

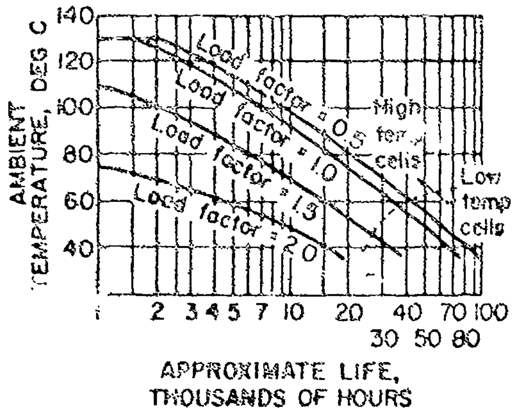


Fig. 1-15 (A). Life expectancy of a typical selenium rectifier as a function of working load and ambient temperature.

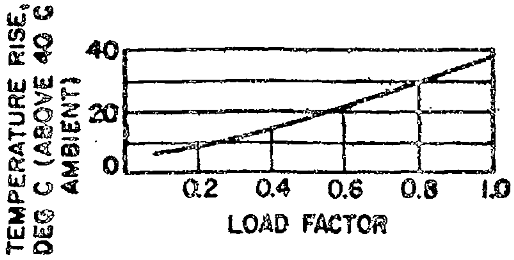


Fig. 1-15 (B). Temperature rise of a three-phase convection-cooled rectifier.

that these curves are typical only. Wide variations exist in the magnitudes and trends of these characteristics for different rectifier samples.

Overload Capacity

One of the advantages of the selenium rectifier is its ability to withstand momentary overloads without harm. Within limits, of course, it is not the current overload that causes ultimate failure but rather the high temperatures resulting from high currents. Therefore, if the duty cycle is sufficiently low, that is, if there is enough off time between overloads so that the temperature of the unit does not rise too high, very great intermittent currents can be taken from the rectifier.

Figure 1-16 shows the overload abilities of a typical rectifier as a function of the on-off cycle. A fivefold overload is permissible if the rectifier is off for 2 minutes after a 6-second on period.

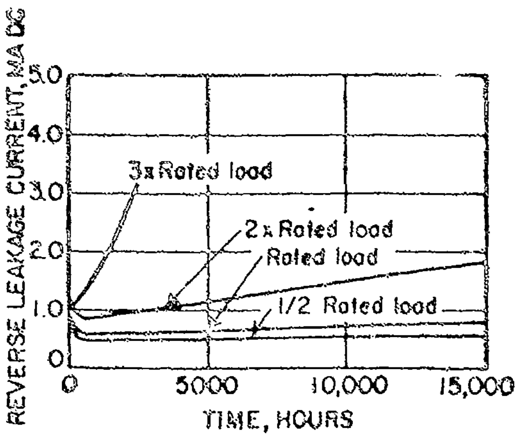


Fig. 1-15 (C). Reverse leakage current vs. operating time. The input voltage and ambient conditions remain constant throughout the test.

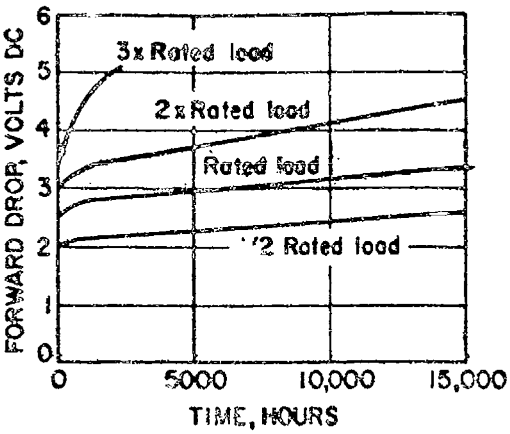


Fig. 1-15 (D). Forward voltage drop vs. operating time. The input voltage and ambient conditions remain constant throughout the test.

Continuous operation at higher than rated current is possible if forced-air cooling is employed. To get still more current, stacks may be operated in parallel. As with any electrical device, suitable means should be provided to divide the load equally among the paralleled stacks.

Derating at High Temperatures

The combination of ambient temperature and a voltage and current rating at which selenium rectifiers give normal life varies with the manufacturer. Whatever is considered as normal, less life can be expected at higher temperatures unless the current and voltage are reduced. Typical derating curves are given in Fig. 1-17, the solid curves represent normal life and the dotted curves represent minimum life of 2000 hours. Another manufacturer gives the following life-expectancy figures.

Actual cell temperature (deg C)	Minimum expected life (hr)
55	Indefinite
65	40,000
75	30,000
80	15,000
90	5,000
100	2,000

Development and use of newer alloys for the counterelectrode has produced rectifiers with considerably longer life at temperatures of 100 to 130 C.

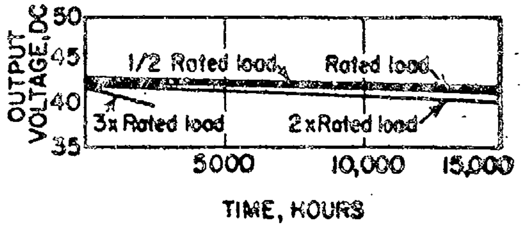


Fig. 1-15 (E). Output volts vs. operating time. The input voltage and ambient conditions remain constant throughout the test.

Voltage Overload

If the rectifier had infinite reverse resistance, voltages higher than normal could be tolerated. However, because of the reverse current which flows through the high reverse resistance, heat is rapidly produced if the voltage is too high. Short-time overloads may be tolerated, but are not recommended. Dielectric punctures may result from severe voltage overloads.

Note from Fig. 1-11 that reverse I^2R losses increase at a rate faster than the voltage increases. Therefore, an increase in voltage above the manufacturer's rated value may result in greatly increased heating. Conservative design dictates that the rectifier have sufficient reserve rating capacity to handle anticipated voltage overloads. For sinusoidal applied voltages and load currents, the rms value of the applied voltage may be applied as a guide. For nonsinusoidal applied voltages and load currents (including half-wave rectifiers with capacitive loads, as are commonly found in voltage multiplier circuits), the peak values of voltage, which the rectifier must handle, must be determined and compared with the peak voltage allowed

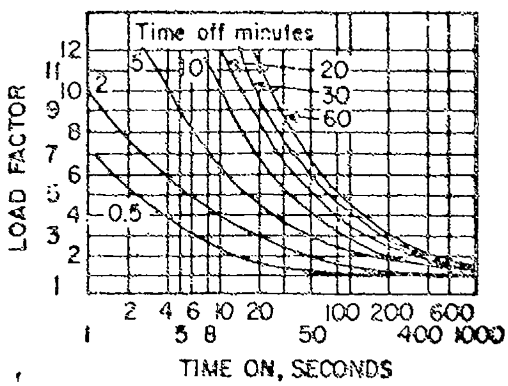


Fig. 1-16. Safe current overloads for intermittent duty.

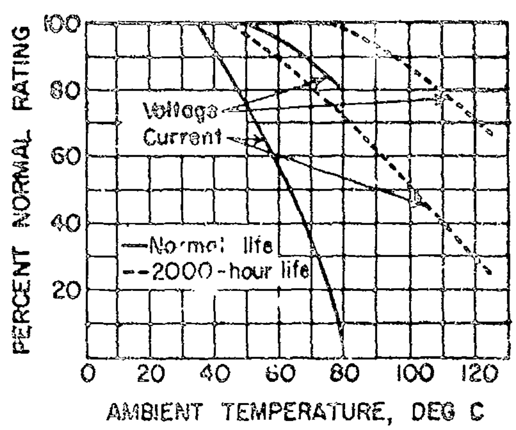


Fig. 1-17. Derating curves for a typical selenium rectifier.

for the rectifier under consideration. The peak allowable values may be considered to be 1.41 times the rms rating of the rectifier unless otherwise stated.

For a resistive or inductive load, the peak of the input ac is readily calculated (for a sine wave of 120 volts, the peak is 169 volts), but if the load includes one capacitor at the rectifier output terminals, the possible peak is double that of the sine wave input (for a sine wave of 120 volts, double peak is 338 volts). For a multiplier circuit which includes capacitors, the peaks must be known and suitable rectifiers employed.

Cooling Methods

The load factor for selenium rectifiers may be safely increased if some method for moving the fluid (air or liquid) between the cells of the stack is employed. Figure 1-18 shows how, using the indicated spacing between the cells, the normal current rating of one manufacturer's selenium stack can be maintained by convection cooling. The spacing shown is suitable for convection cooling of any size cell; cells larger than 4 by 4 inches may use half the indicated spacing when forced-air cooling is used. Forced-air cooling of cells smaller than 4 by 4 inches is not usually done. Forced-air cooling is most effective when the cell spacing is such that the air flow is turbulent rather than laminar; if the cells are too close together, only laminar flow is possible, because the closely spaced fins act as duct baffles to smooth the flow.

Figure 1-19 shows that for a forced-air velocity of 400 feet per minute (fpm), the

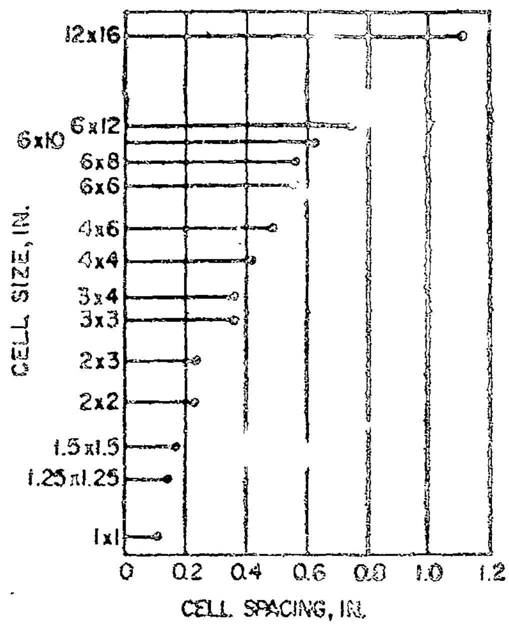


Fig. 1-18. Recommended minimum cell spacing for convection cooling of rectifier stacks.

load factor may be increased to 2.5 if a temperature rise of approximately 35 C is satisfactory. Therefore, a stack of eight 12- by 16-inch, 26-volt cells with a normal current rating of 86 amp in a three-phase bridge can safely handle 86 times 2.5 or 215 amp with

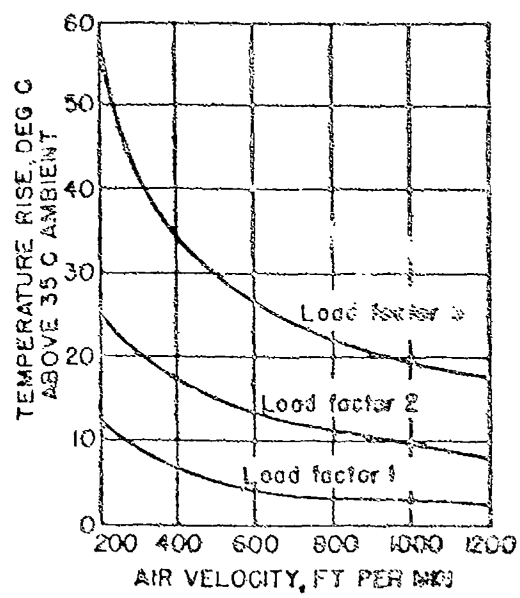


Fig. 1-19. Effect of forced-air cooling on temperature rise of a rectifier stack at various load factors.

400 fpm, since the temperature rise is held to 25 C above a 35 C ambient. The normal current curve is not continued to zero air velocity because stacks designed for forced-air cooling use different spacing than that used for convection cooling. To determine the theoretical volume of cooling air required for a rectifier stack, the lineal feet per second required to pass over the cells should be multiplied by the outline area of the side of the stack that will be perpendicular to the direction of air flow. The plane of the rectifier cells should never be perpendicular to the direction of flow.

It is also possible to immerse the complete rectifier in a tank of oil, in which cooling coils may be provided. In general, oil tanks are used for high-voltage stacks, say 50,000 volts or higher, where insulation as well as cooling is of major importance.

Regulation

The drop in output voltage under load varies with the type of circuit employed. The actual forward voltage drop across a single selenium cell is 2 volts or less. In a typical rectifier, the forward voltage drop varies from about 0.5 volt at half rated current to about 1.8 volts at 4 times rated current. In single-phase full-wave bridge rectifiers, the output voltage at 4 times rated output current may drop about 10 percent compared to the voltage at rated output.

The regulation characteristic of a typical convection-cooled three-phase selenium bridge rectifier is represented by the solid line in Fig. 1-20. The dotted line represents the overall regulation of rectifier plus transformer to be 7 percent from one-tenth to full-load direct current. These curves are based on the assumption that the primary voltage stays constant under load, and that the primary voltage is adjusted to supply 240-volt direct current at full rated load. The curve on Fig. 1-20 is from actual test data; 10 percent regulation is usually guaranteed.

Efficiency

Semiconductor rectifiers are inherently low-resistance devices, and their efficiency is fairly high. Compared to high-vacuum electron tube rectifiers, their efficiency is high because the latter have high internal resistance and, in addition, require power for heating the cathodes, and this power must be figured into the overall efficiency. Figure 1-21 shows the efficiency for a particular manufacturer's product. The overall circuit efficiency is a function of the type of circuit used. Figure 1-21 shows the relative advantage of three-phase full-wave rectifiers compared to a three-phase motor-generator set.

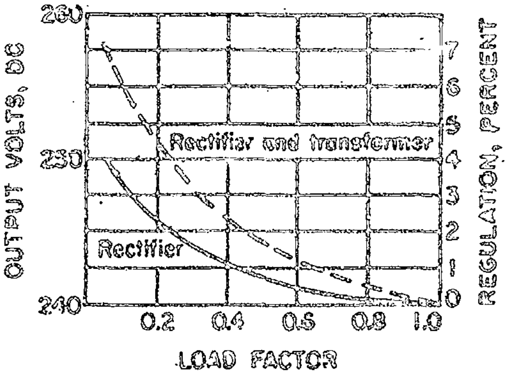


Fig. 1-20. Voltage regulation of a three-phase convection-cooled rectifier.

Efficiency is sometimes called conversion efficiency or conversion ratio, and is the relation between the a-c power applied and the d-c power (measured with d-c averaging meters) secured as a result of the rectification process. Conversion efficiency, as shown in Fig. 1-22, drops as the rectifier load is reduced below full load. This is true because the forward voltage drop is relatively constant up to full load and, at less than rated voltage this drop becomes a larger percentage of the load voltage, hence the efficiency decreases.

Cell Capacitance

The average selenium cell will have an electrostatic capacitance of approximately

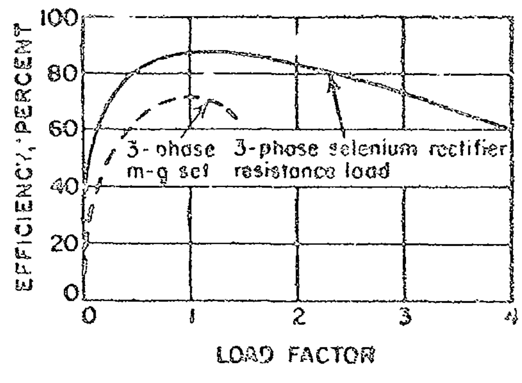


Fig. 1-21. Efficiency curve of a typical three-phase rectifier, working into a resistance load, compared to a motor-generator set.

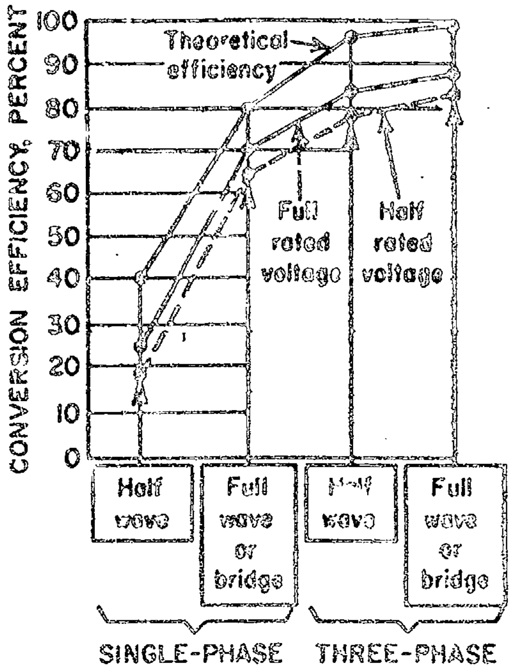


Fig. 1-22. Conversion efficiency of various circuits furnishing direct current to resistance loads.

0.02 mf per sq in. of cell area. This limits the frequency at which such a cell will operate efficiently. Consider a 33-volt cell handling power at a current density of 0.01 amp per sq in. The reverse resistance of a unit of 1 sq in. is, therefore, 3300 ohms. The capacitive reactance of this unit will be equal to this value, 3300 ohms, at about 2400 cps. As a practical matter such a unit will reach its useful operating range at a maximum frequency of about 400 cps, where the reactance is about one-sixth the reverse resistance. This effect is an advantage with capacitance loads.

Naturally the capacitance of any cell is a function of its dimensions. ADN-11050 of 10 June 1953 states: "Selenium rectifiers will deliver power efficiently up to 1000 cps. Above that frequency, they will perform satisfactorily but at reduced efficiency."

Testing

Because a metallic rectifier is not perfect, that is, because it does not have infinite resistance in one direction and zero resistance in the other direction and its resistance in both directions varies with time, testing rectifiers of this type is not simple. In the first place, a value of resistance means nothing unless the conditions of test are indicated. Thus, at what voltage, current, and temperature was the measurement made and how was it made? In the second place, the shape of the rectification curve as well as the absolute values of voltage, current, and resistance determine its operating characteristic.

A d-c voltage-current measurement gives only a single value of resistance. Two radically different units might easily have one common point on their voltage-current curves.

Finally, initial testing of a rectifier can give no information on its life expectancy, since so much depends upon the method of manufacture, the operating environment and temperature, duty cycle, and other factors.

Output Test. The simplest test that can be made is to determine if the rectifier delivers its rated d-c voltage to a load when it is supplied with rated a-c input. This type of circuit is shown in Fig. 1-23. The input voltage is adjusted to the rated value and R is adjusted until rated current flows, whereupon the output voltage is measured.

A-C Tests. So-called dynamic or a-c tests have several advantages over d-c tests: creep effects (change of resistance during test) are less pronounced in rectifiers with a-c applied voltages, the required power supplies are more readily available or easier to construct, and a-c tests give a better picture of the actual performance of the rectifier under actual operating conditions.

Forward Voltage Drop. A simple method of measuring the forward voltage drop is

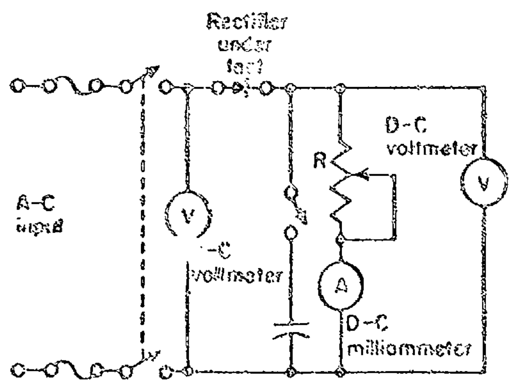


Fig. 1-23. Simple circuit for testing d-c power output.

shown in Fig. 1-24. The transformers should have low internal impedance compared to the minimum rectifier resistance to maintain waveform distortion as low as possible. Either a half-wave rectifying type of instrument calibrated for pulsating direct current or a vacuum tube voltmeter, as shown in Fig. 1-24(C), is recommended.

Reverse Current. A simple reverse-current test circuit is shown in Fig. 1-25 where two rectifiers are connected back to back. In this case, the reverse (leakage) current is the rms current contributed by both rectifiers, and the indicated current will be a composite of the two. Therefore, the rectifier being tested might test good or bad depending upon the "backing" rectifier.

D-C Meter Test. A setup which uses d-c meters exclusively is shown in Fig. 1-26. The test voltage provided is essentially sine wave in form. Resistor R improves the waveform. The bleeder current through R should be at least twice the expected reverse current. The voltmeter indicates the average of the half sine wave of voltage applied to the rectifier under test. The peak voltage, therefore, is the voltmeter reading divided by 0.318.

Combination Test Circuit. The circuit shown in Fig. 1-27 permits readings of forward voltage drop, reverse current, load voltage, and load current under actual operating conditions. The procedure is as follows: With SW1 open and SW2 closed, determine if correct load voltage and current exist. If so, close SW1.

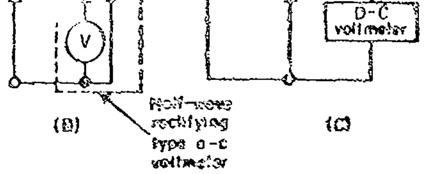


Fig. 1-24. Forward voltage drop dynamic test. (A) Basic circuit. (B) Using a half-wave rectifier. (C) Using a vacuum-tube voltmeter.

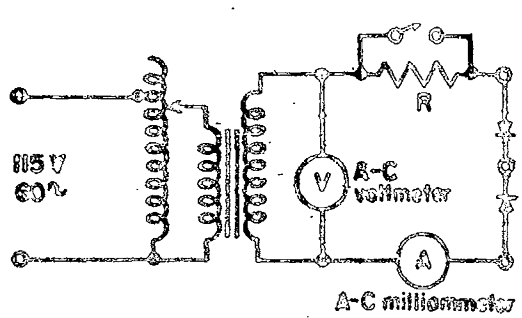


Fig. 1-25. Reverse-voltage test circuit.

If V3 reads zero, the rectifier under test is shorted. If A1 reads zero, the rectifier is open. If forward voltage drop exists, open SW2 and read reverse current.* A high-sensitivity instrument must be used.

SELENIUM RECTIFIER SPECIFICATIONS

MIL-R-11050A

The selenium rectifiers covered by the only coordinated military specification (MIL-R-11050A)† are intended primarily for use in a-c power rectification. They are not designed to become intrinsic circuit components for inclusion in magnetic amplifiers or blocking circuits unless additional requirements are specified.

Voltage, Current and Power Ratings. The specification covers units having continuous d-c current outputs of from 0.100 (half-wave) to 9.600 amp (bridge) at an ambient temperature of 35 C with a resistive load. The maximum number of cells permitted to handle this 9.6 amp load is 12. Voltage ratings from

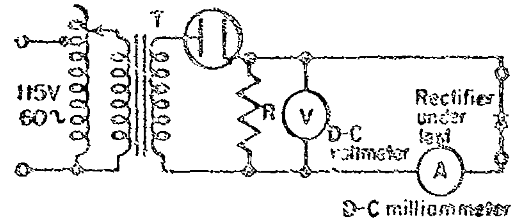


Fig. 1-26. D-C meter test circuit.

*The several circuits for testing rectifiers described above are taken from the Metallic Rectifier Manual, Bradley Laboratories, Inc.

†Publication dated 23 June 1955. There are nine Specification Sheets. These sheets give dimensions, preferred voltage and current ratings. Preferred Parts List, dated 20 April 1956, includes stud mounting types only.

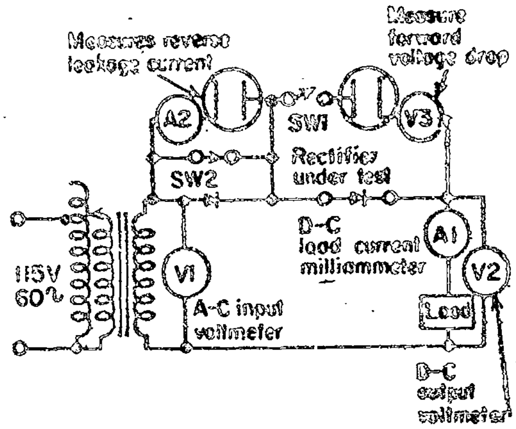


Fig. 1-37. Combination test circuit for use under actual operating conditions.

10 to 400 volts are covered by this specification. Power ratings range from 1.4 watts to over 100 watts, with the number of cells running as high as 40, depending on the continuous power output rating. The stack lengths of these units range from 11/16 to 7-9/16 inches; plate areas from 1.1 to 30.0 sq in. Preferred single-phase styles are half-wave, bridge and center-tapped with stud mounting. All rectifiers procured to MIL-R-11050A requirements are voltage and current derated above 55 C; at an ambient of 85 C these units are voltage derated to 80 percent at zero current. Circuits are given in the specification for testing rectifiers for forward voltage drop and reverse current.

Type Designation System. RS 10 B 100 HS 141 is a typical rectifier designation. Positive terminals are color-coded red; negative terminals are coded black, and neutral (common) terminals are coded yellow.

"RS" identifies the item as a Rectifier, Selenium.

The number "10" identifies the cell size. The various sizes are listed below.

No.	Cell size (in.)
10	1.0 by 1.0
20	1.25 by 1.25
30	1.6 by 1.6
40	2.2 by 2.2
50	3 by 3
60	4 by 4
70	4 by 6
80	5 by 6

The letter "B" identifies the mounting method as a bolt and "S" as a stud.

The number "100" identifies the nominal continuous d-c output voltage rating under a resistive or inductive load (battery or capacitive loads are 20 percent less) at 55 C ambient. The first two digits represent significant figures, and the third digit denotes the number of zeros to follow.

The letters "HS" identify the circuit configuration. The table below lists the various circuits.

Symbol	Circuit
HS	Single-phase, half-wave
CS	Single-phase, center-tap
BS	Single-phase, bridge
DS	Single-phase, voltage doubler
HT	Three-phase, half-wave
CT	Three-phase, center-tap
BT	Three-phase, bridge

The numerals "141" identify the nominal continuous d-c output current rating under resistive load at 55 C ambient temperature. The first two digits represent significant figures in milliamperes, and the last digit denotes the number of zeros to follow.

Electrical and Environmental Requirements. The detailed operating requirements of MIL-R-11050A are given below. These requirements, unless otherwise specified, are based on an ambient temperature of 25 C (+10, -5), 80 percent maximum humidity, sea level air pressure (28 to 32 inches of mercury), and the use of 60-cycle alternating current with the total harmonic distortion not to exceed 7 percent.

Forward Voltage Drop. The forward voltage drop shall not be greater than that specified for the individual rectifier (see MIL-R-11050/1-9) after 5 ± 1/2 minutes of operation at rated current in a suitable circuit as shown on pages 12 and 13 of the specification. It is approximately 3 volts maximum per cell.

Reverse Current. The test requirements are the same as for forward voltage drop. Maximum reverse current allowed is approximately 1/20 of the rated forward current.

Dielectric Strength. The rectifier shall withstand, without arcing, damage, or breakdown, a test potential (shown below) for 1 minute

applied between all current carrying parts connected together and the mounting members. The voltage shall be applied at a rate of not over 500 volts rms per second.

A-C rms voltage (rated)	Test volts (rms)
60 or less	600
over 60 to 90	900
over 90	1000 plus 2 times the a-c rating; (but not more than 3000 volts)

Insulation Resistance. Insulation resistance shall not be less than 100 megohms between all current carrying parts and the mounting members when measured with a 500-volt insulation tester.

Low-Temperature Exposure. The forward voltage drop shall not change more than 8 percent from the initial measured value (imv), and there shall be no peeling of the protective finish when the rectifier is exposed to -55 C (+0, -3) for 3 hours, and then at room temperature for 4 hours.

Low-Temperature Operation. The forward voltage drop at -55 C (+0, -3) shall not change more than 100 percent from the imv, and the reverse current shall not exceed 2 times the specified value after the rectifier is exposed to -55 C (+0, -3) for 3 hours (1 hour nonoperation followed by 2 hours of operation at rated current and voltage).

High-Temperature Operation. The reverse current at 70 C (+0, -3) shall not exceed 2 times the specified value after the rectifier is operated at 80 percent of rated input voltage and 50 percent of rated output current into a resistive load for 4 hours at an ambient temperature of 70 C (+0, -3).

Life Test. The forward voltage drop shall not exceed the specified value after the first hour of operation under rated current and voltage into a resistive load at an ambient of 55 C (+0, -3). The forward voltage drop after 3000 hours of operation shall not change more than 100 percent from the imv. Measurements taken at the end of each successive 250 hours during the test shall show the average rate of change of the forward voltage drop during the last 500 hours to have been equal to or less than the average rate of change during the first 2500 hours.

Moisture Resistance. When tested per MIL-STD 202, Method 106, the forward voltage drop shall not change more than 20 percent from the imv. The reverse current shall not exceed two times the specified value. The insulation resistance shall not be less than 20 megohms, and there shall be no dielectric breakdown.

Corrosion. When tested per MIL-STD 202, Method 101, Test B, the forward voltage drop and the reverse current shall not change more than 8 percent from the imv. There shall be no dielectric breakdown and no peeling of the protective finish.

Mechanical Shock. When tested per MIL-S-901, Figure 6E, Test C, the forward voltage drop and reverse current shall not change more than 5 percent from the imv, and there shall be no dielectric breakdown.

Vibration. When tested per MIL-STD 202, Method 201, for 1 hour in each of three mutually perpendicular directions, the forward voltage drop and reverse current shall not change more than 5 percent from the imv. There shall be no dielectric breakdown and no looseness of parts or other mechanical damage.

MIL-R-14234(SigC)

This is a Signal Corps specification, dated 6 January 1956, which covers high-temperature selenium rectifiers, with essentially the same information and requirements as MIL-R-11050A. Cell size designations differ from the coordinated specification as shown in Table 1-3 and maximum permissible reverse currents are stated.

MIL-R-18281 (Navy)

This specification, dated 15 December 1954, covers selenium, copper oxide, and magnesium-copper sulfide rectifiers for naval ship-

Table 1-3—Data From MIL-R-14234(SigC), Dated 6 January 1956

Style	Size (in.)	Maximum reverse current (ma)	
		Half-wave and center tap	Bridge
RS15	1 × 1	5	10
RS25	1.25 × 1.25	10	20
RS35	1.6 × 1.6	20	40
RS45	2.2 × 2.2	30	60
RS55	3 × 3	60	100
RS65	4 × 4	130	260
RS75	4 × 6	180	360
RS85	5 × 6	230	460

board use. The rectifiers must be designed to operate satisfactorily in an ambient temperature of 50 C, withstand a dielectric strength test of 200 volts rms, and must have an insulation resistance not less than 10 megohms between each circuit, and from each circuit to ground at normal operating temperature.

Electrical and Environmental Requirements. Under this specification, the requirements for forward voltage drop, reverse current, and aging under load are as follows:

Forward Voltage Drop and Reverse Current. The initial average forward voltage drop and average reverse current in a 50 C ambient shall be equal to or less than the initial value indicated in Fig. 1-28, with rated load and voltage for convection cooling. (For example, a selenium rectifier stack with an average forward voltage drop of 2 percent of the rms voltage rating could not have an average reverse current of more than 4 percent of the average current rating.)

Life Performance. After operation for 5000 hours at rated load and voltage in a 50 C ambient, the average forward voltage drop and average reverse current shall be equal to or less than the aged value indicated in Fig. 1-28, with rated load and voltage for convection cooling. (For example, if the selenium rectifier stack under test increased in average forward voltage drop to 3 percent of the rms voltage rating, then the average reverse current could have increased to 6.0 percent of the average current rating.) The increase of the forward voltage drop during the last 500 hours of operation shall not exceed 3 percent of the initial value and the incremental rate of change of both the forward voltage drop and reverse current shall be such as to indicate that the rectifier stack is approaching a stable operating characteristic. The operating characteristics of copper oxide and magnesium-copper sulfide rectifiers are shown in Figs. 1-29 and 1-30 for comparison purposes.

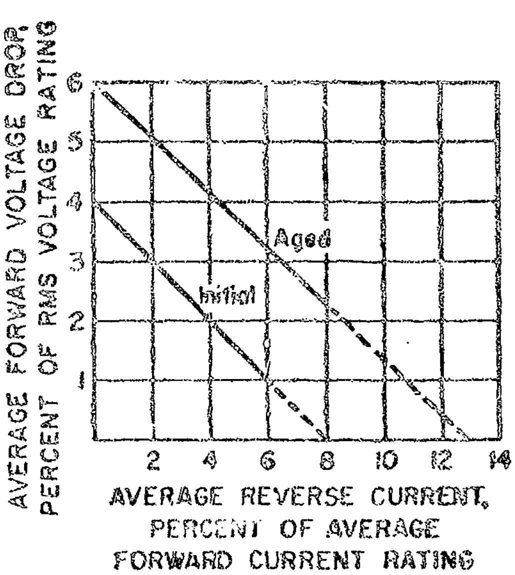


Fig. 1-28. Forward voltage drop vs. reverse current requirements for selenium rectifiers per MIL-R-19381(Navy).

Table 1-4.—Selenium Rectifier Classes per NAS 711

Class	Ambient temperature range at sea level (deg C)
A	-55 to +71
B	-55 to +100
C	-55 to +125
D	-55 to +150

NAS 711

NAS 711, dated 15 March 1955, is a specification of the National Aircraft Standards Committee for selenium rectifiers for use in magnetic amplifiers, 400 cps. Rectifiers are grouped into four classes according to the ambient sea level temperature range and two grades according to their ability to withstand severe environmental conditions as shown in Table 1-4. Grade 1 rectifiers must operate satisfactorily at 50,000 ft altitude, -55 C, as well as withstand humidity and salt spray tests. Grade 2 rectifiers will operate satisfactorily when protected from these conditions.

This specification contains useful circuits and routines for measuring rectifier characteristics.

GERMANIUM AND SILICON RECTIFIERS

Although much of what has appeared earlier in this chapter applies to the newer semiconductor rectifiers as well, the latter are considered as entirely distinct devices.

GENERAL CHARACTERISTICS

Electrical

The nonlinear conduction characteristics of a germanium rectifier can be expressed mathematically by the following equation:

$$I = A(\epsilon^{BV} - 1) \qquad (1)$$

where J = current density through the rectifying junction, amp per sq in.

V = applied voltage across the junction (positive for forward conduction, negative for reverse)

A and B = temperature dependent coefficients.

At room temperature B has a value between 20 to 40 volts^{-1} and A has a value between 0.001 to 0.01 amp per sq cm. The coefficient varies exponentially with temperature, there being approximately ten-fold increase in A for every 30 C increase in temperature. B varies inversely as absolute junction temperature.

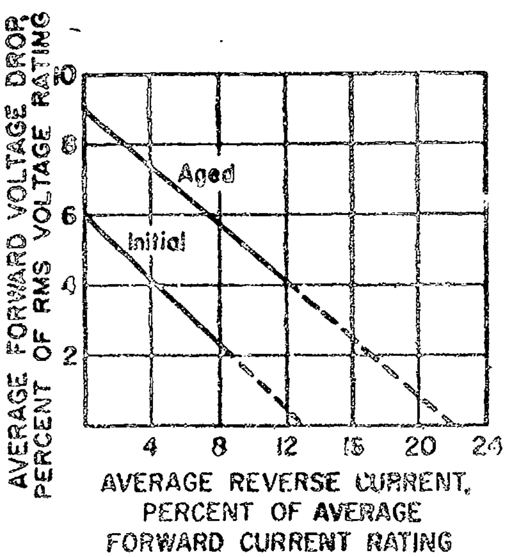


Fig. 1-29. Forward voltage drop vs. reverse current requirements for copper oxide rectifiers.

For example, the forward voltage drop of a typical germanium rectifier at -60 C is about 20 percent greater than at room temperature, and at 75 C is about 10 percent lower than at room temperature. (See Fig. 1-31.)

Equation (1) holds accurately at low-levels of forward voltage or reverse current. With suitable restrictions, discussed below, it can be used throughout the working range of the rectifier's characteristics.

Since the coefficient B is relatively large, for negative applied voltages greater than a

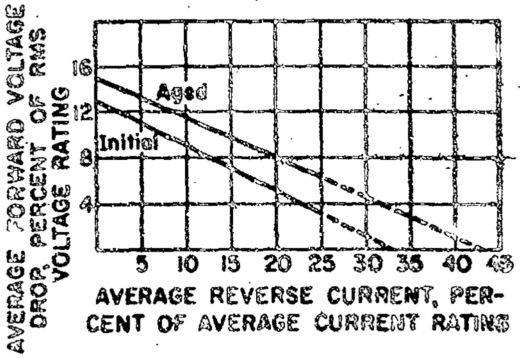


Fig. 1-30. Forward voltage drop vs. reverse current requirements for magnesium copper sulfide rectifiers.

few tenths of a volt, the exponential term becomes small compared to unity and the reverse current density becomes independent of voltage and equal to the constant A. This voltage-independent reverse current is known as the reverse saturation current.

The reverse current, therefore, varies exponentially and rapidly with junction temperature. The rapid increase in current with temperature results in a rigid temperature limitation for the application of a germanium rectifier. Equation (1), which predicts the reverse saturation characteristic, does not include leakage currents which shunt the junction or breakdown currents which may flow at high reverse fields. Thus, the equation is restricted to low level unless these leakage effects are considered separately.

With forward voltage applied to the junction, the exponential term in Eq. (1) becomes large compared to unity; hence, the forward current varies exponentially with applied voltage. This characteristic has such a steep slope that the forward drop of a germanium rectifier can

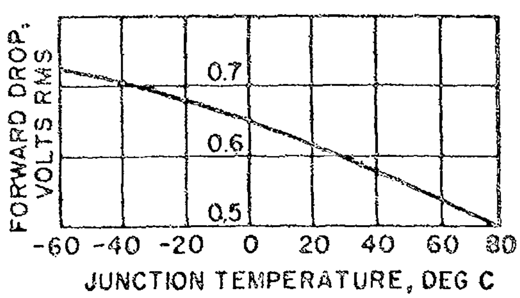


Fig. 1-31. Forward drop plotted as a function of junction base temperature for a 10-amp germanium power rectifier.

be approximated as a constant 0.4 to 0.5 volt over its practical operating range of currents. Equation (1) does not correlate well with experimental data at high-current densities and hence it must be restricted to low current levels. An empirical modification of Eq. (1) in which an apparent resistance is considered in series with the junction will give a mathematical expression for the diode characteristic throughout its useful working range.

In theory, silicon rectifiers should also follow Eq. (1). The principal difference is in the value of the constant A, which is smaller by a factor of 10^{-3}. The constant B remains unchanged. In practice, the low value of A means that reverse leakage effects almost always predominate over the saturation current, and Eq. (1) is thus of little use in predicting the reverse characteristic at lower temperatures. In the forward direction, the EI characteristic for silicon is exponential, as it is for germanium. The differences in A for germanium and silicon result in a higher forward drop for silicon. For germanium and silicon rectifiers of comparable geometry, the forward drop of the silicon rectifier at a given current will be about 0.5 volt higher than the germanium rectifier drop.

Types of Junction Fabrication

Silicon power-supply rectifiers are available utilizing any of three different processes: alloy junctions, diffused junctions, and grown or segregated junctions. Germanium rectifiers are made only by the alloy process at present.

Alloy Junction. Alloy junctions are made by fusing a metal with appropriate impurity properties onto one surface of a semiconductor having a conductivity type (n or p type) opposite to that produced by the impurity metal. The metal alloys with the impurity

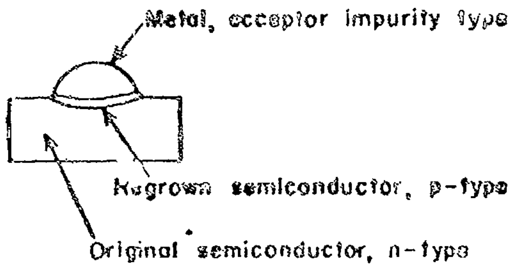


Fig. 1-32. Elements of p-n junction.

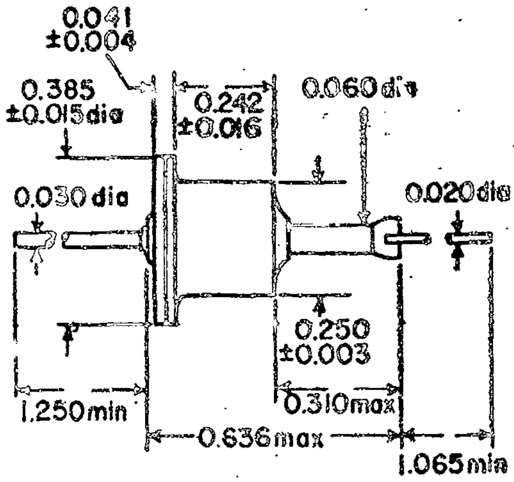


Fig. 1-33. Small coaxial lead mounted package. This package is soldered directly into the circuit. Heat dissipation is by free convection and radiation. It is used for germanium rectifiers of current ratings of about 0.25 amp at 55 C or for silicon rectifiers of current ratings to 0.25 amp at 150 C. (General Electric Co.)

and, upon cooling, the semiconductor regrows at the undisturbed interface. This regrown semiconductor contains impurity atoms of the metal which convert it to the opposite type from the original semiconductor. Thus a p-n junction is formed at the interface between the regrown and the undisturbed semiconductor. This structure is shown in Fig. 1-32.

Germanium alloy rectifiers are conventionally made by alloying indium into n-type germanium; silicon rectifiers are usually made by alloying aluminum or aluminum alloys into n-type silicon. The use of indium for germanium junctions imposes a relatively low storage-temperature limitation since the melting point of the junction structure is +155 C.

Alloy junction structures have the advantage of being easily fabricated. Their chief disadvantage is that the junction may be under mechanical stress because of differential thermal expansion of the metal and semiconductor. This problem is not severe in germanium because of the ductility of the indium alloy, but in most large-area silicon rectifiers it is necessary to back up the aluminum alloy with some material such as molybdenum, which matches the expansion coefficient of silicon. This design results in a sandwich structure for the junction.

Diffused Junction. In this process, impurity atoms are diffused at temperatures near the melting point of silicon into a silicon wafer whose conductivity type is opposite to that of the impurity used in diffusion. This solid-state diffusion results in the conversion of a surface layer of the silicon wafer to the opposite conductivity type, thus forming a junction within the original silicon wafer. Electrical contacts can be made to the silicon surfaces by any of a wide choice of solders since these solders have no effect on forming the junction. The region of the junction is not mechanically disturbed.

Grown Junction. In this process, a p-n junction is produced in a single crystal by

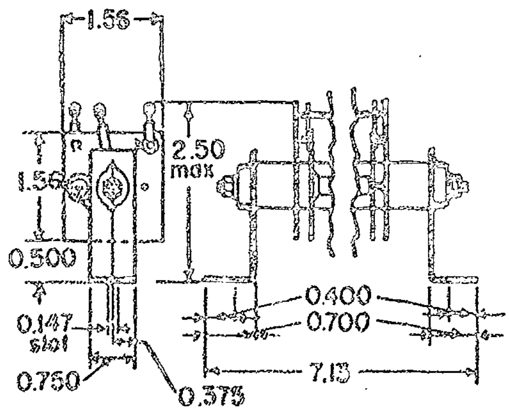


Fig. 1-34. Small cell on fin. This rectifier is fabricated by mounting the single cells on a fin. The rating is increased because of the improved heat transfer. The fins may be stacked for series or paralleling as for a specific multirectifier configuration such as a bridge. (General Electric Co.)

varying the concentration of impurity atoms during the growth process. This is costly, but it has an advantage in that the transition from p to n type can be made gradually rather than abruptly, resulting in a device with inherently higher reverse breakdown characteristics.

Packaging

The basic problem in the design of these newer power rectifiers is one of heat transfer. Therefore, the chief difference in low- and high-power rectifiers is one of package design. The process of junction formation differs little for low- or high-power rectifiers; the only significant variation is the junction area.

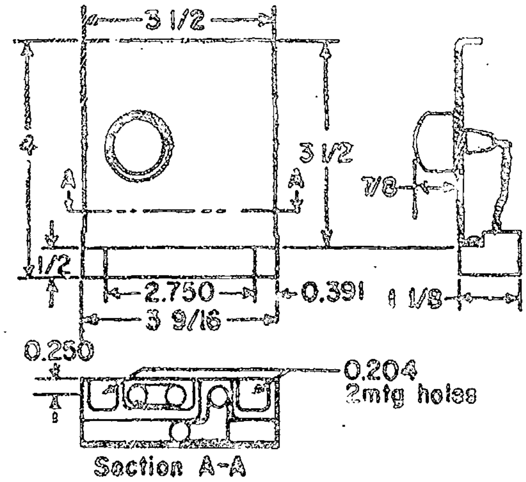


Fig. 1-35. Large cell on single fin. The unit is rated at up to 10 amp (germanium). The fins may be stacked. Heat transfer is by radiation and either free or forced convection. (General Electric Co.)

Examples of typical package designs are shown in Fig. 1-33 through 1-39.

Thermal Stability

The voltage drop across a rectifier while it is conducting causes junction heating in proportion to the product of current and voltage drop. For a constant load current, this forward heating decreases slightly as the junction temperature rises. A typical variation of

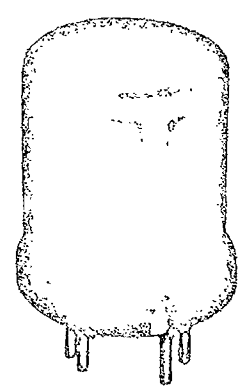


Fig. 1-36. Plug-in type rectifier. (Texas Instrument Co.)

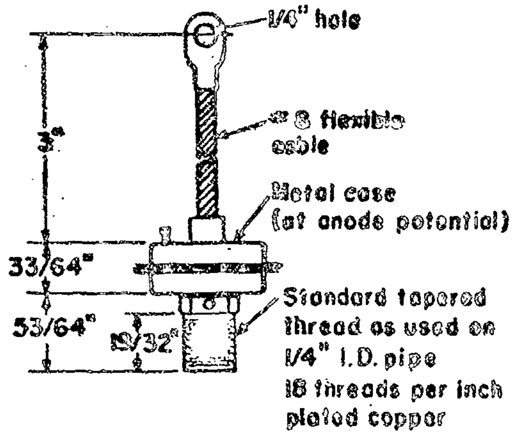


Fig. 1-37. Stud-mounted cell. This high-current silicon rectifier is a single cell built on a stud-type heat sink. It is used in many sizes for silicon rectifiers of ratings from 0.5 to 250 amp. Heat transfer is by conduction to an external heat sink. (General Electric Co.)

average forward heat (P_f) vs. junction temperature is shown in Fig. 1-40.

Heating of the junction during the nonconducting, blocking or reverse part of the cycle is proportional to the product of the inverse voltage and the reverse* current leakage through the junction. Since the reverse current varies in an approximately exponential manner with increasing junction temperature, the average heating due to a reverse current resulting from a fixed inverse voltage waveshape can also be expected to vary exponentially. Curve P_r in Figure 1-40 depicts such a variation. Curve P_t represents total heating, the sum of forward and reverse heating.

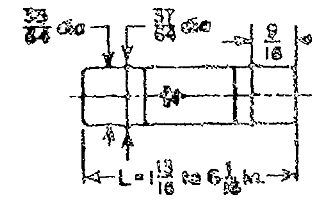


Fig. 1-38. Cartridge-type rectifier. This rectifier package consists of a ceramic cartridge similar to a fuse cartridge which contains one or more rectifier junctions. The package is especially suited for series-connected cells to form a high-voltage rectifier assembly. (International Rectifier Corp.)

* In germanium and silicon literature, the terms "reverse" and "inverse" are used interchangeably.

Under steady-state conditions, the generation of heat at the junction due to forward current and inverse voltage is balanced by the flow of heat through the cooling system. This flow causes a temperature rise of the junction above ambient equal to the product of the power and the thermal impedance of the cooling system. Curve P_d in Fig. 1-40 illustrates this essentially linear variation of junction temperature rise versus heating power. The junction of the rectifier cell will stabilize at the point at which the power generation curve P_t and power dissipation curve P_d intersect, that is, when heat dissipation exactly balances heat generation.

Under conditions such that these two characteristics do not intersect, the junction temperature cannot stabilize, but increases to a point where either melting of cell materials or thermal stresses cause cell failure. Such unstable or runaway conditions can be caused by voltage or current overloads, restricted cooling, excessive ambient temperatures, or deterioration of the reverse blocking characteristic of the unit. The maximum vertical overlap ΔP of curves P_d and P_t is a measure of the reliability of a particular application. To secure longer life expectancy, ΔP can be increased by derating voltage and/or current per cell, by improving cooling, and by providing lower ambient temperatures.

Thermal runaway of the type described usually requires that the temperature of the entire cell and its associated cooling system "run away" from the ambient temperature. Such action requires the lapse of many minutes because of the large thermal masses involved. Under very severe overloading, however, failure may occur within a matter of cycles as the very limited thermal capacity of the junction materials allows the junction to run away from the temperature of the cooling system.

Maximum Junction Temperature

When thermally stable conditions prevail, the maximum internal operating temperature of any type of rectifier cell is limited to the lowest melting point of its components. However, if long life and high reliability are required under continuous-duty operating conditions, the temperature of the junction must usually be limited to a value well below the minimum melting point to insure an ample safety factor for unusual voltage and current transients that may occur in service.

The temperature at which a silicon or germanium junction may operate satisfactorily

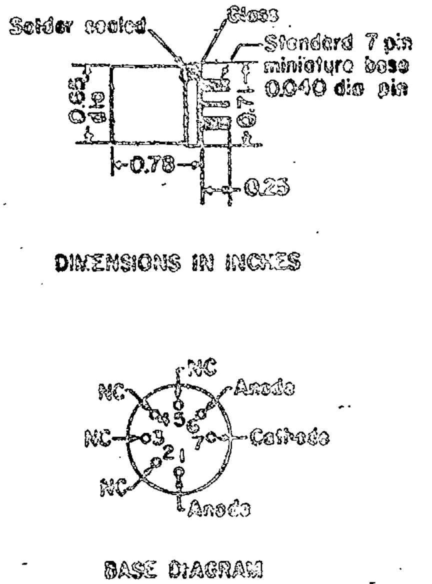


Fig. 1-39. Plug-in package similar to tube envelope. This package was designed for high-voltage silicon grown junctions to directly replace a vacuum tube.

depends also to a great extent on its design and fabrication. High temperatures promote chemical contamination on the delicate and minute surfaces of the junction. This chemical activity deteriorates the voltage blocking ability of the rectifier to the point where breakdown or thermal runaway eventually occurs.

Two alternatives, or a combination of both, can protect the junction from this possibility. One is to limit junction temperature to such a low value that chemical activity is reduced to a negligible rate. The other, more direct approach is to eliminate the contaminating foreign agents from possible contact with the junction. This can be accomplished by extreme care in fabrication, chemical or electrolytic etching of the junction, and rigorous cleaning processes; all to rid the device of initial contamination, and finally, use of a hermetic seal to keep subsequent environmental contamination away from the junction during the lifespan of the cell. Reproducibility of these techniques is one of the major problems confronting the manufacturers. Careful attention to these cleanliness factors permits troublefree operation at junction temperatures in excess of 100 C for germanium cells and 200 C for silicon cells provided the application does not introduce the possibility of thermal runaway.

Peak Inverse Voltage

Although exceeding the PIV rating of a silicon or germanium cell does not imply certain destruction of the cell, operation in this area can lead to reduced life through eventual thermal runaway or voltage breakdown, or a combination of both.

In some cells, particularly small-area silicon devices, the reverse EI characteristic displays a sudden rapid increase in reverse current when a given voltage is exceeded. In other cells, notably germanium and large-area silicon devices, a "softer" or gradual breakdown in the reverse characteristic occurs. In either case, this increase in reverse current can lead to overheating, excessive cell deterioration, and thermal runaway, particularly when aggravated by such external factors as current overloads and higher-than-normal ambient temperatures.

Because of the very close relation of PIV and ambient temperature on the possibility of thermal runaway, particularly in germanium devices, the manufacturer often offers alternate ratings by which the user can trade PIV for higher operating temperatures or vice versa.

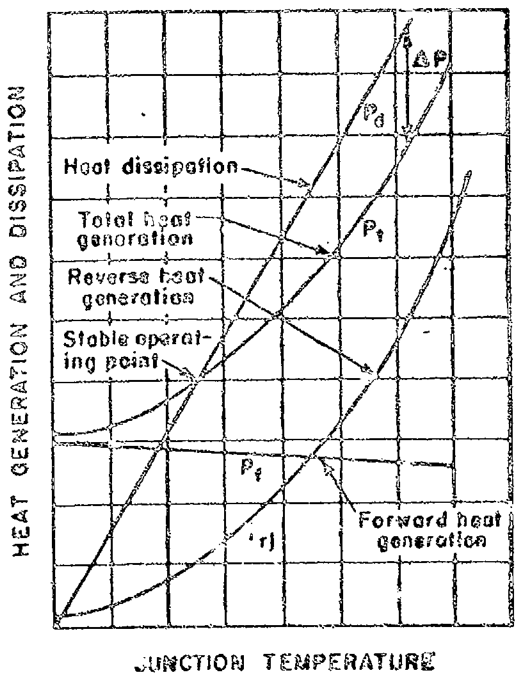


Fig. 1-40. Heat relations in junction rectifier (from Proposed Test Code for Metallic Rectifiers, AIEE No. 59).

Inductive Load Effects

When any rectifier supplies an inductive load from a highly reactive a-c line, special protection against induced voltages which exceed rated PIV may be necessary. Under these conditions, the rectifier cell commutates its load to the next leg very suddenly. A charge of current carriers is left stranded in the bulk semiconductor material. These carriers (holes in n-type bulk material) normally disappear by recombination with electrons or by diffusion out of the semiconductor material. However, when reverse voltage is applied immediately after heavy forward current conduction, these carriers do not have time to recombine and diffuse naturally, but instead are swept across the junction into the p-region, resulting in a current limited only by source impedance. Until the carriers have been completely swept out of the bulk semiconductor, the resistance of the cell is very low, acting almost like a short circuit. Within a few microseconds after reverse voltage has been applied, the carriers have all been swept out and the cell recovers abruptly. Its resistance immediately changes from a fraction of an ohm to thousands of ohms, causing a substantial voltage surge to be induced in the line reactance. Since this is a cyclical occurrence, it is important to protect the cells from these voltages if they are excessive. A small amount of capacitance installed across the d-c output terminals of the rectifiers in full-wave circuits, or across the a-c input terminals of half-wave circuits, will usually dampen the most vicious voltage spikes to values within rectifier handling capabilities. This problem appears most prevalent in magnetic amplifier applications where it is imperative that reverse current be kept to a minimum.

Surge Conditions

The foregoing discussion concerned itself largely with silicon and germanium cells operating under continuous-duty conditions. The rectifier cell, however, will frequently be subjected to intermittent application of additional current and voltage, the severity of which will depend on the application.

Fortunately, the inherent thermal capacity of the rectifier cell can be utilized to good advantage in absorbing the additional heat generated by transient overloads of current. For transients of a few cycles, the thermal capacity of the junction itself will permit severe overloading before it reaches excessive temperatures. Manufacturers' data on this type of duty is available in the form of surge curves or overload characteristics. A curve showing allowable surge current for a typical silicon rectifier is shown in Figure 1-41.

Under extremely high currents that the rectifier can withstand for less than one or two cycles, the rectifier acts essentially like a resistance. Under these circumstances, a maximum safe value of integrated heating or Σi^2t, can be established for the cell from manufacturers' data. Since fuses essentially display this same constant i^2t characteristic, they are a handy tool for protection. For cells that are subject to thermal runaway, the maximum allowable i^2t will depend upon the inverse voltage impressed on the cell following the overload.

The continuous PIV rating of a silicon or germanium cell should not be exceeded even under momentary conditions, unless the manufacturer specifies a separate transient PIV rating. (See Tables 1-5 and 1-6.)

SILICON AND GERMANIUM RECTIFIER APPLICATION CONSIDERATIONS

Fault Protection

Fault protection requires special consideration in designing germanium or silicon rectifiers because of their relatively low thermal capacity. Most manufacturers supply overload or surge characteristics of their cells which show current handling capacity as a function of time for short duration overloads. Any protection system must limit fault currents to values specified by the surge curve. This may be accomplished by introducing sufficient impedance in the circuit to limit the fault current to safe values, or by paralleling a sufficient number of cells so that the current through any one cell does not exceed its rating. A single fuse or circuit breaker may be used in the load circuit or in each a-c line for load fault protection.

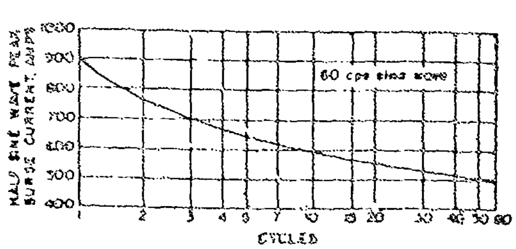


Fig. 1-41. Maximum allowable surge current at maximum rated load conditions for a typical silicon power rectifier.

Table 1-6—Typical Silicon Rectifier Characteristics

	1N536	1N537	1N538	1N539	1N540	4JA60C*	4JA60B*	4JA60A*	4JA60F*
Max peak inverse voltage	50	100	200	300	400	300	200	100	50
Max rms voltage	35	70	140	210	280	210	140	70	35
Max continuous reverse voltage	50	100	200	300	400	—	—	—	—
Max d-c output, ma, at 150 C	250	250	250	250	250	†	†	†	†
Max d-c output, ma, at 50 C	750	750	750	750	750	†	†	†	†
One-cycle surge current, amp	15	15	15	15	15	600	[illegible]	600	600
Full-load forward voltage drop	0.5	0.5	0.5	0.5	0.5	‡	‡	‡	‡
Max leakage current, ma	0.4	0.4	0.3	0.3	0.3	50¶	50¶	50¶	50¶
Max operating frequency, kc	50	50	50	50	50	—	—	—	—
Ambient operating temperature, deg C	-65 +165	-65 +165	-65 +165	-65 +165	-65 +165	-65 +200	-65 +200	-65 +200	-65 +200
Storage temperature, deg C	-65 +175	-65 +175	-65 +175	-65 +175	-65 +175	-65 +200	-65 +200	-65 +200	-65 +200

*Commercial-type numbers.
† Depends on temperature. Range (dc) = 100 amp at 103 C to 6 amp at 200 C.
‡ At 25 C: 0.6 volts at 0.1 amp, 1 volt at 50 amp, 1.7 volts at 500 amp.
At 200 C: 0.3 volts at 0.1 amp, 1 volt at 100 amp, 1.7 volts at 500 amp.
¶ At max PIV, 200 C junction temperature.

In addition, fuses are generally used to isolate a defective cell when continuous operation of equipment is mandatory. In such an arrangement, the cells in each leg of the circuit are divided into several parallel groups with a fuse in series with each group. When a cell failure occurs, fault current from other legs flows through the failed cell and its fuse until the fuse opens, leaving the other groups still operable. A minimum of three groups per leg is generally required to ensure that the proper fuse will fail.

Table 1-8—Typical Germanium Power Rectifier Characteristics

					1N315			4JA3011B*	
	1N91	1N92	1N93	1N368	55 C	71 C	85 C	55 C	85 C
Max peak inverse voltage	100	200	300	200	300	200	100	200	100
Max d-c output current, ma	150	100	75	100	75	100	100	[illegible]	2100
Max forward voltage drop	0.5	0.5	0.5	0.48	0.40	0.45	0.44	0.32	0.25
Max leakage current at rated PIV, ma	2.7	1.9	1.2	0.3†	—	—	—	10	15
Continuous reverse working voltage, dc	30	65	100	150	150	100	50	200	65
Max rms voltage	--	--	—	--	--	—	--	140	70
Min forward to reverse current ratio (avg forward to avg reverse current at full load)	--	--	--	—	700	300	300	--	—
Power dissipation, full load	--	--	--	--	—	--	--	4	2
Operating frequency, kc	50‡	50‡	50‡	50‡	50‡	50‡	50‡		
Max surge current, amp	25	25	25	--	--	--	--	120	100
Storage temperature, deg C	85	85	85	85	95	95	95	105	105

*Commercial-type number.
† At 150 volts dc.
‡ 70 percent rectification.

Series and Parallel Operation

When a higher peak inverse voltage must be handled than can be tolerated by a single cell, series operation may be employed. The recommendations of the manufacturer should be followed in such a case because some types of cells require matched characteristics to operate in series reliably. Resistors may be used in parallel with series cells to ensure voltage sharing but this practice may be uneconomical and will generally reduce the overall system reliability.

Cells may also be connected in parallel for greater current handling capacity. Careful matching of characteristics is required to achieve satisfactory current division. Division can be forced by the use of a series resistor with each cell but this results in reduced circuit efficiency and is usually not done.

Cell losses can be determined quite accurately in any circuit by graphical integration of the product of cell voltage and current waveforms. Direct measurement can also be accomplished in low-frequency circuits through the use of a low-power-factor moving coil wattmeter. Such a meter must be able to respond to the d-c component of the waveform as well as the harmonic components.

Mechanical Considerations

Silicon and germanium rectifiers are inherently rugged mechanically because they are small in size and contain no moving parts. Most types can withstand vibration fatigue tests of 10 g and 1-millisecond shocks of 500 g. The cooling system associated with a rectifier cell is generally weaker, mechanically, than the cell itself. The only types requiring care in orientation are free convection-cooled fin types and internal vapor-cooled types.

Thermal Considerations

The losses incurred in operating a rectifier cause its temperature to rise above that of the ambient. Since the losses are concentrated in the region of the rectifying junction, junction temperature is often used in rating a rectifier.

An indirect measuring technique is used with junction temperature, which is inaccessible for direct measuring. The power loss in the cell is multiplied by its internal thermal impedance to obtain the internal temperature rise. Thermal impedance is generally specified by the manufacturer as the temperature rise (per watt) of the junction above an external temperature reference point.

To ensure satisfactory operation of a semiconductor rectifier, adequate cooling must be provided. Where natural convection cooling is employed, the proximity of other hot objects must be considered. Rectifiers designed for natural convection cooling often depend on losing a considerable amount of heat by radiation. A nearby hot object may cause a substantial reduction in radiation loss.

Forced-air convection improves the maximum continuous current rating of a rectifier but does not increase the short-time surge rating. Forced convection does not improve the absolute maximum PIV rating, but may reduce the derating factor where required to prevent thermal runaway. Considerable work is in progress on liquid cooling for large germanium power rectifiers.*

RELIABILITY AND LIFE

Causes of Failure

Germanium and silicon rectifiers may fail in service due to a number of reasons.

1. Thermal runaway as a result of inadequate cooling or excessive current or voltage.

2. Melting of rectifier materials by overcurrents such as occur during faults.

3. Fracture of junction materials or solder ...s due to thermal fatigue or temperature ...k.

4. Deterioration of reverse characteristic as a result of junction surface contamination, either remaining from fabrication and processing or permitted to enter through defective hermetic seals. This deterioration usually leads to thermal runaway.

5. Fracture of solder joints or fault currents of sufficient magnitude to melt and disperse internal materials.

In properly fabricated cells, no change in the forward characteristic has been known to occur with the passage of time.

*Wahl, R. E., "Direct Water Cooled Germanium Power Rectifier," Communication and Electronics, AIEE, January 1957.

Means of Prolonging Life

Reliability of semiconductor rectifiers can be improved by increasing the thermal runaway margin of safety. Better cooling, reduced peak-inverse voltage and less forward current loading will accomplish this. A large factor of safety will reduce the probability of failure due to unplanned abuses in the field and will allow greater deterioration of the cell before runaway will occur. Chemical deterioration of the cell also takes place at a slower rate at low temperatures. The practice of using rectifiers in series greatly improves reliability since the general mode of failure is to short rather than to open. The life survival pattern for a typical germanium rectifier is shown in Fig. 1-62.

Accelerated Life Tests

Accelerated life testing of semiconductor rectifiers can be accomplished by operating with a reduced thermal runaway factor of safety. Failures occur more frequently than normal because less margin for reverse deterioration is available. Another technique frequently used is storage at elevated temperatures above the normal operating (junction) temperature. This causes the reverse characteristic to deteriorate at an accelerated rate even though the cells are nonoperative.

STANDARDS AND SPECIFICATIONS

Professional and Industry

A comprehensive tabulation of germanium and silicon rectifier terms, symbols, and tests may be found in the "IRE Standards of Electron Devices: Definitions of Semiconductor Terms, 1954"; "IRE Standards on Letter Symbols for Semiconductor Devices, 1956"; the standards of the Committee on Semiconductor Devices (JTC-14) of the Joint Electron Tube Engineering Council (JETEC); and the Proposed Test Code for Metallic Rectifiers (AIEE). In the growing technology of germanium and silicon devices, some conflicts with the established terms and practices of selenium and copper oxide rectifiers will occur temporarily but further work will bring uniformity of standards and specifications.

Military

MIL-E-1, "Electron Tubes and Crystal Rectifiers"; MIL-T-25380A(USAF), "Semiconductor Diodes, Photodiodes, Transistors and Phototransistors"; and MIL-T-12679A(SigC), "Transistors, Crystal Diodes and Related Semiconductor Electronic Devices" are basic specifications which include terms, symbols, and electrical, mechanical, and environmental tests for rectifiers.* MIL-STD-202, "Test Methods for Electronic and Electric Component Parts" covers both simulated and accelerated environmental tests. Semiconductor rectifiers are frequently specified in terms of references to the environmental parts of equipment specifications of the three branches of armed services. Typical environmental specifications would include requirements for some or all of the following: mechanical shock, centrifuge, high-frequency vibration, vibration fatigue, salt spray (corrosion resistance), humidity, moisture resistance, temperature cycling, high-temperature storage, low-temperature storage, altitude, and pressure. Further special requirements, such as resistance to nuclear radiation, fungus, rain, sun, and sand, may be added. Also, tests (for example, axial strain or glass-envelope strain) applicable to a specific rectifier design are often included. Environmental or design requirements are checked by testing samples from a lot of rectifiers.

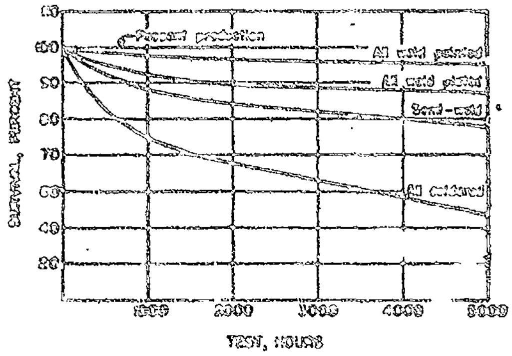


Fig. 1-62. Life survival pattern for a germanium rectifier.

Life tests are generally treated separately from environmental tests because of the long time consumed and the necessary low level of sampling. Life tests may be performed at any temperature. However, they are normally performed at the highest operating temperature (which results in the severest conditions).

TRENDS AND DEVELOPMENTS

Semiconductor rectifiers will be improved considerably during the next few years. Semi-

*MIL-T-19500A, "Transistors, General Specification," has replaced MIL-T-25380(USAF) and will replace MIL-T-12679A.

cally, the trend is toward more efficient, higher temperature, higher voltage, more reliable, and less expensive rectifiers. Future developments are listed below.

1. Longer Life. A better understanding of the factors which cause degradation is being gained with experience. Reverse current leakage around the junction has been the most difficult factor to bring under control. However, processes which minimize or eliminate exposure to moisture and other contaminants plus better packages should alleviate this problem. With the elimination of leakage around the junction and proper mechanical construction, essentially infinite life should be realizable.

2. Higher Environmental Reliability. Better mechanical designs and good process control will result in more reliable devices under extreme environmental requirements.

3. Higher Power Capabilities. Units capable of carrying up to 2000 amp per cell are already under consideration. A number of cells in the 250-amp range are rapidly reaching production stages.

4. Lower Cost. The cost per kilowatt of rectified power using germanium and silicon rectifiers is rapidly becoming competitive with other types of rectifying cells. As the volume of units sold increases, both raw materials and process costs will decrease.

5. Greater Operating Temperature Range. Better process and package design for silicon rectifiers will result in permissible operation up to 250 C. Other semiconductors are being studied which should permit operation at temperatures considerably in excess of 250 C.

6. Nuclear Radiation Resistance. Radiation resistance becomes more important with the growth of nuclear power. Several studies are in progress to determine radiation effects on semiconductors now in production. In addition, efforts to design radiation-resistant rectifiers have been started.

7. Improved Characteristics. Both the reverse and forward characteristics will be improved as manufacturing experience is gained.

8. Higher Reverse Voltage Capabilities. Some silicon rectifiers for use in excess of 1000 volts have already appeared on the market. Under normal ambient conditions, silicon rectifiers can offer much higher reverse voltage capabilities than germanium rectifiers. This feature, more than any other, will cause a definite trend toward the use of silicon rectifiers. For very high voltage rectification, graded instead of alloy junctions will undoubtedly become the standard.

9. Special Designs for Specific Applications. New designs will become available as a result of demands for specific semiconductor characteristics; for example, for voltage reference or regulator rectifiers. Others, such as high-frequency rectifiers and rectifiers which behave like thyratrons, are already being designed.

SELENIUM, GERMANIUM, AND SILICON RECTIFIER APPLICATION CONSIDERATIONS

Electrical Circuit

The ratings of rectifier cells are primarily determined by internal heating.* Therefore, when cells are applied in a specific circuit, the waveshapes of applied voltage and current must be considered for their heating effects. Thus, a capacitive-input filtered circuit would impose a lower average rating for a given cell than would a resistive or inductive load. Similarly, the reverse voltage waveform imposed by a three-phase circuit will cause greater reverse heating than a single-phase circuit with the same peak-inverse voltage.

Rectifier circuit tables such as Table 1-7 give the theoretical relationships of current and voltage for the commonly used power-supply circuit connections. These relationships are based on the assumptions that the supply voltage is a true sine wave and that the rectifying cells present no circuit losses.

The effects of cell voltage drop on output voltage can be determined from the published values of full-cycle voltage drop. The voltage will be less than the theoretical value of the circuit by the amount of cell drop determined as follows:

Total cell drop = Number of circuit legs times the number of series cells per leg times the average cell drop.

This method will be sufficiently accurate for most circuits. Exceptions are low-voltage supplies where the cell drop becomes a significant percentage of the output voltage.

* Other than those imposed by the reverse breakdown voltage of the cell, which is not usually a limiting factor.

Table 1-7—Characteristics of Rectifiers and Rectifier Circuits°

Rectifier connection	1-phase half-wave	1-phase full-wave center-tap	1-phase full-wave bridge	3-phase half-wave	3-phase full-wave bridge	3-phase diametric (6-phase star)	3-phase double-wye (with IPT)
No. of rectifying elements required	1	2	4	3	6	6	6
Rectifier characteristics to obtain 1.0 volt 1.0 amp d-c output							
Rectifier output characteristics							
Average d-c volts	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Peak d-c volts	3.14	1.57	1.57	1.21	1.05	1.05	1.05
Rms d-c volts	1.57	1.11	1.11	1.02	1.00	1.00	1.00
Ripple factor	1.21	0.48	0.48	0.18	0.042	0.042	0.042
Major ripple frequency	1F	2F	2F	3F	6F	6F	6F
Rectifying element characteristics—Resistance load without filter							
Average forward current (per rectifying element)	1.00	0.50	0.50	0.333	0.333	0.167	0.167
Peak forward current (per rectifying element)	3.14	1.57	1.57	1.21	1.05	1.05	0.525
Rms forward current (per rectifying element)	1.57	0.785	0.785	0.587	0.579	0.409	0.293
Ratio: peak per average forward current	3.14	3.14	3.14	3.63	3.15	6.30	3.15
Peak inverse volts	3.14 E_{dc}	3.14 E_{dc}	1.57 E_{dc}	2.09 E_{dc}	1.05 E_{dc}	2.09 E_{dc}	2.42 E_{dc}
Rectifying element characteristics—Large reactor-input filter or inductive load							
Average forward current (per rectifying element)		0.50	0.50	0.333	0.333	0.167	0.167
Peak average current (per rectifying element)		1.00	1.00	1.00	1.00	1.00	0.500
Rms forward current (per rectifying element)		0.707	0.707	0.577	0.577	0.408	0.289
Ratio: peak per average forward current	—	2.00	2.00	3.00	3.00	6.00	3.00
Peak inverse volts		3.14 E_{dc}	1.57 E_{dc}	2.09 E_{dc}	1.05 E_{dc}	2.09 E_{dc}	2.42 E_{dc} ¶
Transformer rating—Large reactor-input filter or inductive load							
Rms secondary volts per leg	2.22†	1.11	1.11	0.855	0.427	0.740	0.855
Secondary rms amperes	1.57†	0.707	1.00	0.577	0.816‡	0.408	0.289
Primary rms amperes	1.57†	1.00	1.00	0.471	0.816	0.577‡	0.408
Secondary volt-amperes	3.49†	1.57	1.11	1.48	1.05	1.81	1.48
Primary volt-amperes	3.49†	1.11	1.11	1.21	1.05	1.28‡	1.05
Average volt-amperes	3.49†	1.34	1.11	1.35	1.05	1.55‡	1.26
Secondary utilization factor	0.287†	0.637	0.90	0.675	0.955	0.551	0.675
A-C line input—Large reactor-input filter or inductive load							
Rms amperes	1.57†	1.00	1.00	0.816‡	1.41‡	0.816‡	0.707‡
Power factor	0.287†	0.90	0.90	0.827	0.955	0.955	0.955
Max theoretical efficiency, %	40.6	81.2	81.2	96.5	[illegible]	99.8	99.8

° Table 1-7 was adapted from a table in "Electronics for Industry," by W. I. Bendz, John Wiley & Sons, Inc., New York, 1947.

† Values for resistance load without filter.

‡ Values for Delta connected primary.

¶ Max inverse peak volts at light load.

RECTIFIER LOAD CONSIDERATIONS

Single-Phase

Loads. Rectifier loads may be categorized as resistive, inductive, and capacitive, and various combinations of these types. The effect of the load upon the output waveform, peak current, and so on, is as follows.

Resistive. For single-phase circuits, the voltages and currents specified are for resistance loads. These are the simplest to calculate because there can be no storage of charge in a resistor. Therefore, the maximum inverse voltage (E_m) across the rectifier is the peak of the applied a-c voltage; for a sine wave, E_m equals E_{peak} equals 1.41 E_{rms}.

On Fig. 1-43 the sine wave instantaneous value is $e = E_m \sin \theta$

$$\theta = 2\pi ft$$

where

E_m = peak voltage
θ = phase angle, radians
f = frequency, cps
t = time, seconds

Figure 1-43 shows the resistance load voltage of a half-wave rectifier. The average value is E_{av} equals 0.318 E_m.

Inductive. The inductive load causes no special problems other than those associated with circuit interruption. Typical inductive loads are relay coils, filter chokes, and so forth. (See also "Inductive Load Effects" under Silicon and Germanium Rectifiers.)

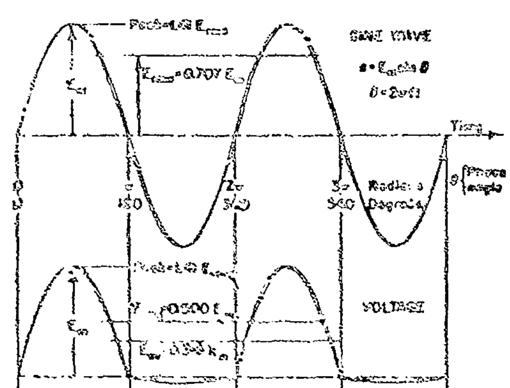


Fig. 1-43. Waveforms in a single-phase half-wave rectifier with resistance loads.

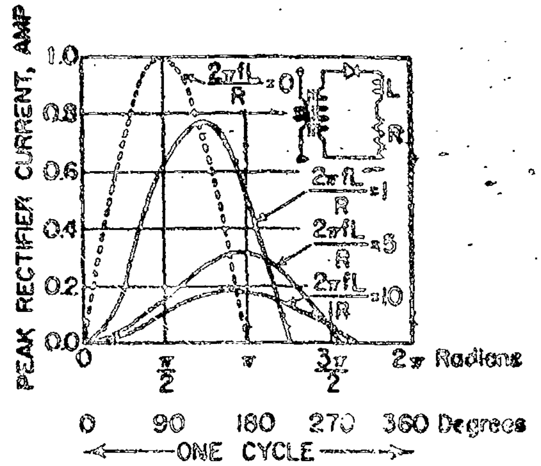


Fig. 1-44. Effect of inductance on reducing peak rectifier currents in single-phase half-wave circuits.

1. De-energized coil. A de-energized coil acts like an open circuit. When voltage is applied, current builds up in it as the magnetic field becomes established. During continuous operation, the coil keeps the current flowing steadily, but there is no voltage problem. In general, the inductive-load rectifier circuit has the same current rating as the resistance load, and the peak inverse voltage across the rectifier is, as with resistance loads, the peak of the a-c supply voltage.

One cycle of the current wave shown on Fig. 1-44 represents an inductor and series resistor supplied from a half-wave rectifier. When the inductance is zero, the dotted curve, which is typical for resistance loads, is followed. When $2\pi fL/R$ equals 1, a smaller peak current is obtained, and the current continues to flow past the 180-degree phase angle. The load resistance is kept constant for all curves on Fig. 1-44. As the inductance value is increased, the peak current is decreased, and the time of current flow is lengthened. Inductive loads are seldom used on half-wave rectifier circuits. Often they are supplied from full-wave single-phase or any of the three-phase circuits.

2. Inductive kick on opening d-c circuits. When deenergized, the circuit inductance must dissipate its stored energy. It is dangerous to open a d-c series-inductor circuit; the inductive kick can do damage. Instead, the approved method is to open the a-c circuit to the rectifier. Then the inductive kick will quickly and harmlessly dissipate itself in the rectifier. This is the principle of the arc suppressor.

Capacitive. This type of load is typified by high-peak inverse voltages and high-surge currents. The precautions noted below should be closely followed for best performance and life.

1. Current derating factor. For all single-phase rectifier circuits, the resistance-load current rating should be decreased to 0.8 for capacitive or battery loads. A rectifier rated at 2-amp resistance load, will handle a 1.6-amp capacitor load. One reason for this derating is that an uncharged capacitor is a short circuit; it takes a heavy initial charging current. This should be limited by a series resistor, usually of the order of 1 percent of the actual load resistance. This is so small that it does not materially affect d-c operation. In addition, there is considerable storage of charge in a capacitor, which at no-load rises to the peak of the applied a-c voltage; or 1.41 E_{rms}.

2. Charging current. For all useful loads, some current is drawn so that the capacitor discharges to a voltage below the peak value. The voltage E_{dc} across the capacitor is the solid line curve on Fig. 1-46(B), and the applied voltage for a full-wave rectifier is the dash curve. Starting from the left, E_{dc} drops to point F where it intersects the rising a-c wave. At this point, the rectifier starts to supply current as shown on the lower part of Fig. 1-46(B). The rectifier continues to conduct until point G is reached, where E_{ac} again reaches the E_{dc} value, and no further conduction occurs until Point F is reached on the next half wave. As shown, the peak current I_m is K times the average current I_{av}. This factor K is indicated on Fig. 1-46. With large capacitors, and d-c voltages near the a-c peak value, heavy peak currents are drawn from the rectifier for a short part of the cycle. Selenium rectifiers are better equipped to handle this peak than tube rectifiers mainly because of the inherent capacitive effect of the cell which rounds off the sharp peaks. This is indicated by the dash line at H on Fig. 1-46(B). The peak is usually less than eight times the average load direct current, and the 0.8 derating factor usually is adequate compensation.

3. Reverse voltage peak. With capacitive loads, the reverse voltage applied to a half-wave rectifier will be a maximum of twice the a-c peak; that is, for sine-wave input,

$$E_{reverse\ peak} = 2.83\ E_{rms}$$

This is because the capacitor stores a d-c peak of 1.41 E_{rms} and on the next half-wave

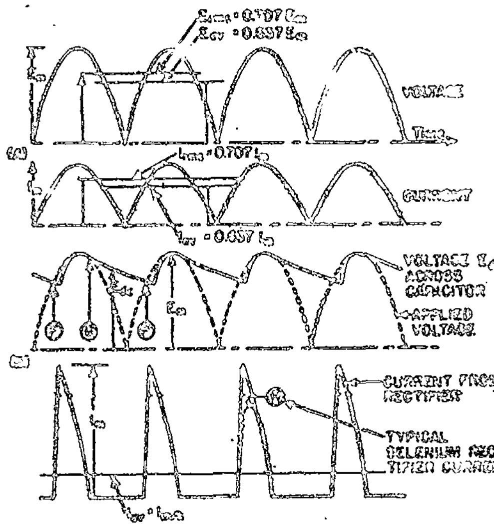


Fig. 1-45. Waveforms in single-phase full-wave rectifiers with resistive loads (A) and capacitive loads (B).

the transformer input peak is 1.41 E_{rms} in the opposite sense. Specifically, for a 120-volt rms input, the peak inverse voltage which the half-wave rectifier must withstand is 2.83 times 120 or 340 volts. This is typical of half-wave a-c/d-c circuits when operated on alternating current.

4. Series resistor. The series resistor, mentioned earlier as being important during the initial charging of the capacitor, is also needed to reduce the peak currents which are characteristic of capacitor loads. This is particularly true when the d-c voltage is a large fraction of the peak applied a-c voltage.

5. Capacitor load characteristics. Figure 1-46 applies when a rectifier supplies a capacitor load of 4 mf or larger. The rectangular boxes along the bottom represent the input resistances which include both the rectifier and the source (transformer). At the right are ratios K of peak rectifier currents to the average d-c load current.

For example, with 100 input ohms and 10,000 load ohms, the output d-c volts will be 1.3 times the rms input volts from the transformer. The peak current required by the rectifier will be 8.3 times the average d-c load current (right-hand scale).

In contrast with other types of rectifiers, in particular mercury vapor diodes where the tube rating must not be exceeded, the peak current is seldom of consequence with sele-

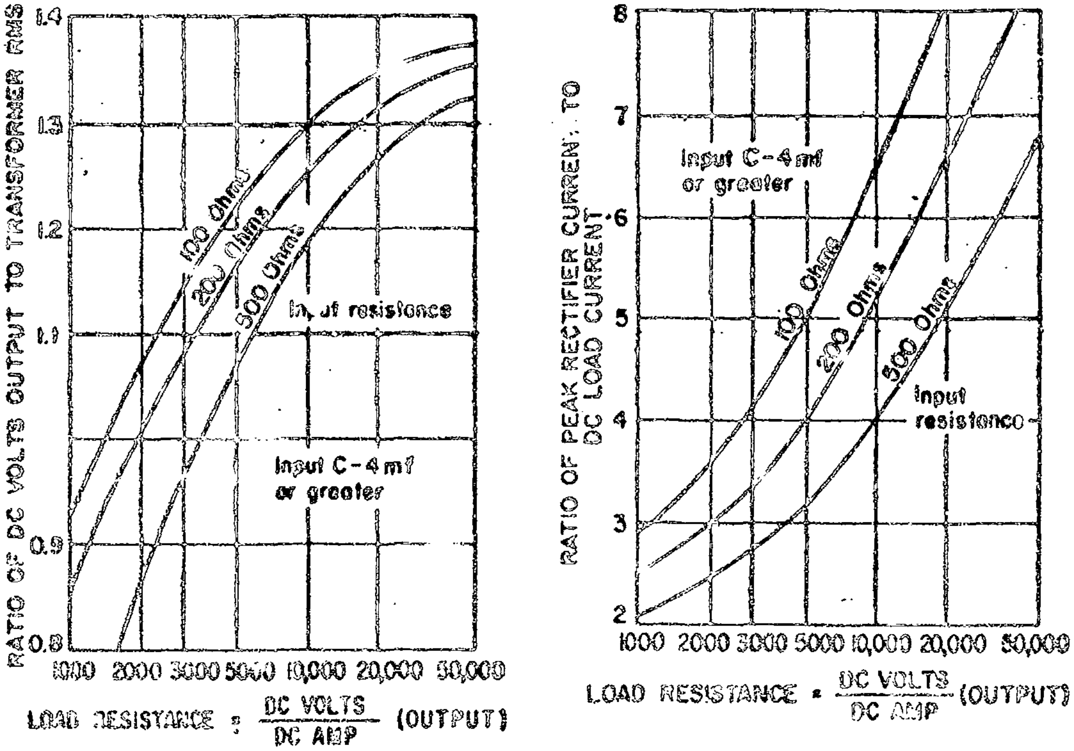


Fig. 1-46. Operating characteristics of single-phase full-wave rectifiers with 60-cps a-c supply and with capacitive loads greater than 4 mf. (ARRL, The Radio Amateur's Handbook, 33rd. ed., 1956)

nium rectifiers; the average current is more important.

Figure 1-47 shows the regulation for various circuits with capacitive loads operating from a 120-volt 60-cycle input.

Battery Loads. The notes for capacitive loads apply directly to battery-charging loads. The voltage of a storage battery remains relatively constant even during the period when there is no charging current from the rectifier. Hence, for half-wave the inverse voltage peak must be regarded as twice that of the peak applied alternating current. For single-phase battery charging, the current rating is 0.8 times the normal resistance load rating.

Circuits. The majority of selenium rectifier circuits operate either from single-phase or three-phase a-c inputs. Table 1-8 gives the characteristics of selenium stacks and circuits. As a rule, the single-phase rectifier circuits are for low-powered applications. The high output ripple is smoothed to a very low ripple by using filters.

Half-Wave. Figure 1-45 "H" is a half-wave rectifier where the applied alternating voltage is E_{ac}, the average direct current through the load is I_{dc}, and the average direct voltage across the load is E_{dc}. The alternating current I_{ac} is in series with I_{dc}. These currents are read by an a-c meter and a d-c meter, respectively. For a resistance load the relations are

$$E_{ac} = 2.3\ E_{dc} + N(Dv)$$
$$I_{ac} = 1.57\ I_{dc}$$
$$\text{Ripple frequency} = f$$
$$\text{Approximate ripple} = 121\ \text{percent}$$

N(Dv) indicates N cells in series, each with an rms forward voltage drop per cell of Dv (see Fig. 1-10).

An advantage of the half-wave rectifier is that the secondary of the supply transformer and one side of the d-c load are common, and can be grounded. This is a valuable safety measure. The disadvantage of the half-wave rectifier is the large d-c component in the transformer secondary. This must be considered in the transformer design.

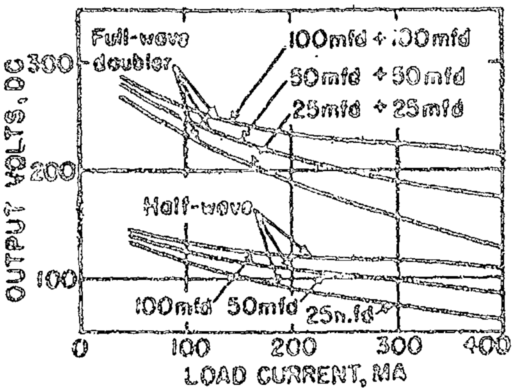


Fig. 1-47. Regulation characteristics of half-wave and full-wave circuits with capacitive loads. Input is 120 volts, 60 cycles.

Full-Wave, Center Tap Positive or Negative. Figure 1-48 "C" and "N" are full-wave center-tapped rectifiers. The center-tapped transformer ... ving power has no steady direct current i... winding, and each half supplies $E_{ac}/2$ for its half cycle. For a resistance load

$$E_{ac}/2 = 1.15\, E_{dc} + N(Dv)$$
$$I_{ac} = 0.785\, I_{dc}$$
$$\text{Ripple frequency} = 2f$$
$$\text{Approximate ripple} = 48 \text{ percent}$$

The alternating current from each half of the transformer secondary is I_{ac} which is read with an a-c ammeter. An advantage of the center-tap circuit is that the transformer tap and one d-c lead can be grounded. This is a normal safety precaution. The cost of the center tap is a disadvantage.

Full-Wave Bridge. An advantage of the center-tapped circuit is obtained with the bridge circuit B on Figure 1-48 because there is no steady direct current in the transformer secondary. Another advantage is that the elimination of the center tap reduces cost. On the other hand, one side of the d-c load, or one side of the transformer secondary, but not both, may be grounded. Usually the negative d-c lead is grounded. For a resistance load

$$E_{ac} = 1.16\, E_{dc} + N(Dv)$$
$$I_{ac} = 1.15\, I_{dc}$$
$$\text{Ripple frequency} = 2f$$
$$\text{Approximate ripple} = 48 \text{ percent}$$

The half-wave and full-wave rectifiers are of major interest in electronic applications, but the output ripples of 122 and 48 percent respectively require a filter.

Voltage Multipliers

Doubler. Figure 1-49 shows several doubler circuits. Twice the alternating voltage peak will be obtained at no-load. Circuits A through D are half-wave doublers. Circuit E is the only full-wave doubler. All doubler circuits require capacitors so that the peak inverse voltage rating of the rectifier must be doubled.

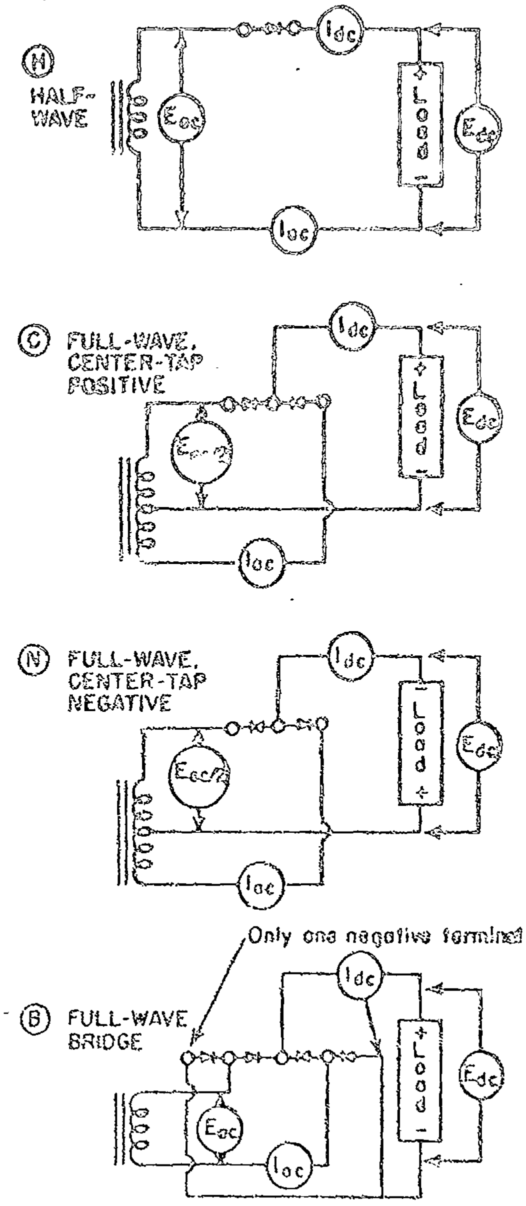


Fig. 1-48. Single-phase rectifier circuits.

Table 1-8—Characteristics of Rectifier Stacks and Circuits

Single-phase resistance loads	A	Circuit	Figure	V	Input I_{ac}	Input E_{ac}	Output E_{dc}	Output I_{dc}	I_A	Ripple (%)
Half-wave	1	E	48	1.41 E_{ac}	1.57 I_{dc}	2.2 E_{dc} + N Dv	0.45 (E_{ac} − N Dv)	0.64 I_{ac}	0.64 I_{ac}	121
Full-wave center-tap	2	C, N	48	0.707 E_{ac}	0.79 I_{dc}	2.2 E_{dc} + 2N Dv	0.45 (E_{ac} − 2N Dv)	1.27 I_{ac}	0.637 I_{ac}	48
Full-wave bridge	4	B	48	1.41 E_{ac}	1.11 I_{dc}	1.11 E_{dc} + N Dv	0.87 (E_{ac} − N Dv)	0.87 I_{ac}	0.44 I_{ac}	48
Multiphase all loads										
Three-phase half-wave	3		51	2.45 E_{ac}	0.58 I_{dc}	0.85 E_{dc} + N Dv	1.17 (E_{ac} − N Dv)	1.73 I_{ac}	0.58 I_{ac}	18
Three-phase center-tap six-phase star	6	A	52	0.707 E_{ac}	0.41 I_{dc}	1.48 E_{dc} + 2N Dv	0.68 (E_{ac} − 2N Dv)	2.44 I_{ac}	0.41 I_{ac}	4
Three-phase full-wave bridge	6	B	53	1.41 E_{ac}	0.82 I_{dc}	0.74 E_{dc} + N Dv	1.35 (E_{ac} − N Dv)	1.17 I_{ac}	0.408 I_{ac}	4

A — Number of separate rectifying arms, characteristic of a particular circuit. For a full-wave single-phase bridge, A equals 4.
Dv — Voltage drop per cell for a specified circuit.
E_{ac} — Applied rms voltage input, sine wave.
E_{dc} — Average d-c voltage output.
I_A — Average direct current in amperes per rectifying arm A.
I_{ac} — Applied rms current input (amperes).
I_{dc} — Average d-c load current output (amperes).
N — Number of series cells in any one rectifying arm A.
V — Maximum inverse applied a-c voltage to any one rectifying arm A.

Note: Stacks are sometimes identified by three digits also; for instance, 4-2-1 for a single-phase full-wave bridge, two cells in series in each arm, one cell in parallel each arm.

1. Common a-c/d-c lead. On circuit A of Fig. 1-49*, one side of the a-c input and the d-c negative output are common, but C_1 and C_2 capacitors have no common terminal. When the top a-c lead is positive, C_2 is charged; when the top a-c lead is negative, C_1 is charged. After a brief startup period, the voltage on C_1 is added to the voltage applied to the rectifier and C_2, thus doubling the peak voltage at no-load. For circuit B of Fig. 1-49, the d-c positive is common with one side of the input.

2. Common capacitor leads. Circuit C of Fig. 1-49† is of interest because the negative leads of C_1 and C_2 are common, permitting a single-container construction. Circuit D is similar to circuit C, except that the common capacitor leads are positive. For circuits C and D there is no load common to both the load and the input alternating current.

3. Series capacitors. Circuit E of Fig. 1-49 is a full-wave doubler, where each capacitor, C_1 and C_2, is charged on an alternate half wave of the a-c input, and both are discharged in series through the load. This full-wave doubler has the best regulation of the doubler circuits shown. Since it may be considered as two half-wave circuits back to back, the doubler will have twice the voltage drop as each component half-wave circuit. For the full-wave doubler, any one of several points may be grounded. Often this is the point X, so that a positive voltage above ground and a negative voltage below ground are available. This particular arrangement is typical of precipitator systems.

4. Series resistors. As a final note on the circuits of Figure 1-49, whenever capacitors are in the circuit, a series resistor is important. This prevents the large initial surge of current when the capacitors are uncharged, and just as important, it limits the peak current which occurs at each half-cycle of operation. R may be 5 to 100 ohms for most doubler circuits of 1 to 500 d-c ma.

Quadrupler Circuits. Voltage quadruplers employ a series of half-wave rectifiers to deliver a load voltage approximately four times the a-c input voltage. At no-load each section rectifies and stores the peak inverse voltage developed across the rectifier of the previous section. Considering n as a stage of

*U. S. Patent 1,945,334.
†U. S. Patent 2,173,962.

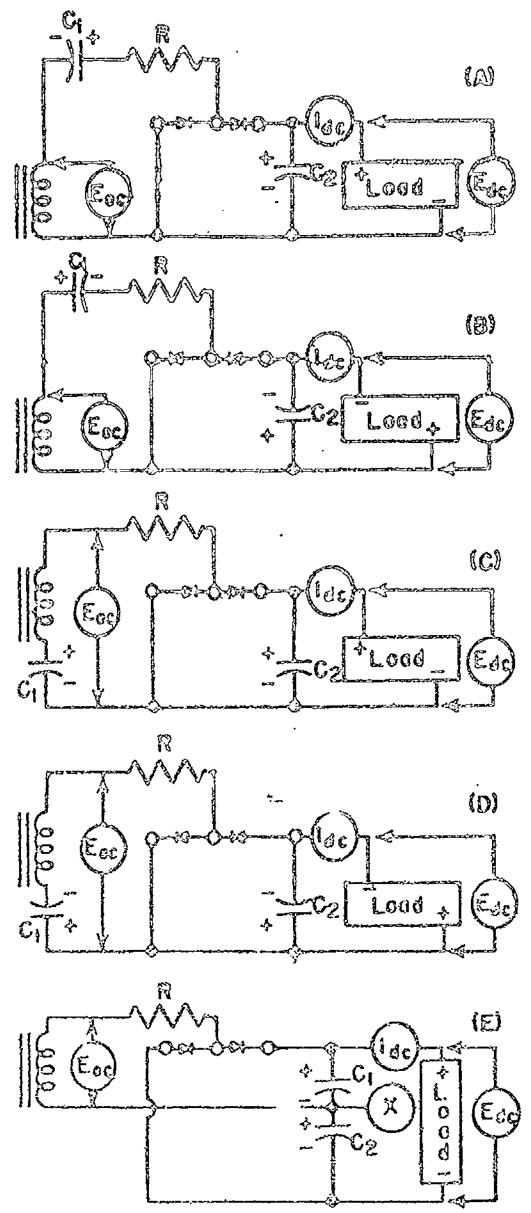


Fig. 1-49. Single-phase voltage-doubler circuits.

doubling (each n takes 2 capacitors and 2 rectifiers), the voltage drop V under a steady load of I amperes is*

$$V = (I/fC)\,(2n^3)/3$$

where f is cps and C is farads. This shows that the drop is directly proportional to the load current and inversely proportional to the frequency times the capacitance.

Figure 1-50 shows two quadrupler circuits, with a peak no-load d-c output of 5.66 E_{ac} volts, where E_{ac} is the rms a-c input voltage. Each of these circuits may be extended to any required number of stages.

1. Series fed. Figure 1-50(A) is a series-fed quadrupler, the peak inverse voltage of each rectifier is 2.83 E_{ac}. The peak voltage across each capacitor, except C_1, is 2.83 E_{ac}; the peak voltage across C_1 is 1.41 E_{ac}. Each capacitor carries a different instantaneous value of alternating current; C_1 has 4I, C_2 has 3I, C_3 has 2I, and C_4 has I. For this reason it is customary to use capacitor values of

$$C_1 = 2C_2 = 3C_3 = 4C_4$$

2. Parallel fed. Figure 1-50(B) is a parallel-fed quadrupler where the currents through all the capacitors, except C_4, are alike and equal to 2I. Through C_4 the current is I. The peak inverse voltage of each rectifier is 2.83 E_{ac}. The peak voltages across the capacitors are: C_1 has 1.41 E_{ac}, C_2 has 2.83 E_{ac}, C_3 has 4.24 E_{ac}, and C_4 has 5.66 E_{ac}. One feature of Fig. 1-50(B) is that C_1 and C_3 have com-

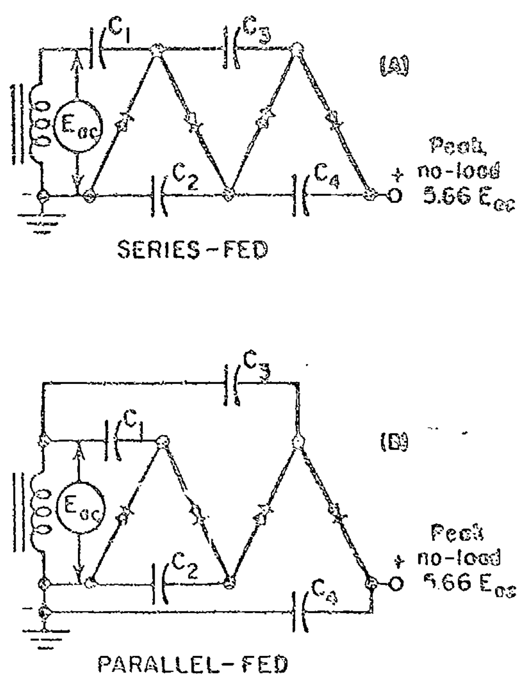


Fig. 1-50. Single-phase voltage-quadrupler circuits.

* Walker, A. B. H., Wireless World, May 1948.

mon negative loads. The common lead of C_2 and C_4 may be the d-c minus lead for the equipment, and ground.

Filters. Single-phase rectifiers are largely used for electronic circuits where smoothed direct currents of 0.1 to 500 ma are required. Since even the lowest ripple factor is 48 percent (see Table 1-8), a filter must be provided to smooth the ripple to an acceptable value. Figure 8-25 shows one section of each of the filter types in common use. As a working guide, d-c currents from 50 to 500 ma use LC filters, and currents from 0.1 to 100 ma use RC filters. The range from 50 to 100 ma can use either filter.

Three-Phase Circuits

Most medium- and high-powered metallic rectifier applications use three-phase circuits. One of the major reasons is the low ripple in the d-c output. For a three-phase full-wave arrangement, the ripple is only 4 percent without filtering. The characteristically low ripple content also makes three-phase circuits more suitable for some low-power applications. Not only is it simpler to filter the output, but the lack of ripple indicates that the heavy inrush of current to a capacitor load, always true of single-phase rectifier circuits, is not present. Although the three-phase half-wave circuit has the highest ripple of all three-phase arrangements (19 percent), generally all three-phase circuits are rated alike for all loads, regardless of their individual ripple content. This illustrates the superiority of three-phase rectifier circuits, since the lowest ripple content available in single phase circuits is 48 percent, which requires derating for capacitor and battery-charging loads.

Half-Wave. Two three-phase half-wave circuits are shown on Fig. 1-51. For all loads,

$$E_{ac} = 0.86\ E_{dc} + N(Dv)$$
$$I_{ac} = 0.586\ I_{dc}$$
$$\text{Ripple frequency} = 3f$$
$$\text{Approximate ripple} = 19 \text{ percent}$$

The disadvantage of the three-phase half-wave, as with the single-phase half-wave circuit, is that direct current flows in the transformer secondaries. It is seldom used, with the exception that the two circuits, shown in Fig. 1-51 can be used together to form the more attractive three-phase circuit with no direct current in the transformer as shown in the top diagram of Fig. 1-52.

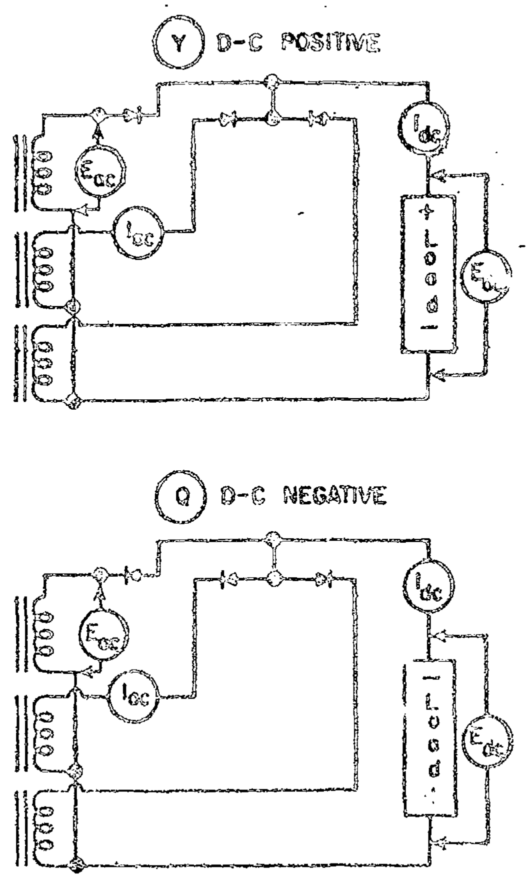


Fig. 1-51. Three-phase half-wave circuits.

Full-Wave Center Tap. The circuit shown in Fig. 1-52 (top) is also known as six-phase star, and carries the highest current rating of the three-phase circuits. For all loads,

$$E_{ac}/2 = 0.74\ E_{dc} + N(Dv)$$
$$I_{ac} = 0.41\ I_{dc}$$
$$\text{Ripple frequency} = 6f$$
$$\text{Approximate ripple} = 4 \text{ percent}$$

The center tap removes steady direct current from the transformer secondaries. A major advantage of this circuit is that the center taps of each transformer secondary and one d-c lead are common and can be grounded.

Full-Wave Bridge. A popular three-phase circuit is shown in the bottom diagram of Fig. 1-52. No steady direct current flows in the secondaries, and the ripple is only 4 percent. The expense of a center tap is eliminated. The d-c load is usually grounded; none of the transformer secondaries may be

grounded. In this case

$$E_{ac} = 0.74\ E_{dc} + N(Dv)$$
$$I_{ac} = 0.85\ I_{dc}$$

Ripple frequency = 6f

Approximate ripple = 4 percent

Figure 1-53 shows three-phase rectifier waveforms.

PRACTICAL CONSIDERATIONS FOR USING RECTIFIERS

The following material may aid design engineers to apply rectifiers so that the reliability of the equipment for which the devices supply power is not unduly compromised. The recommendations are the result of years of experience with selenium rectifiers and are arranged so that material applying to all types of rectifiers comes first followed by specific data on selenium units. There is not yet sufficient experience with germanium and silicon units to be as specific as is possible with the older materials.

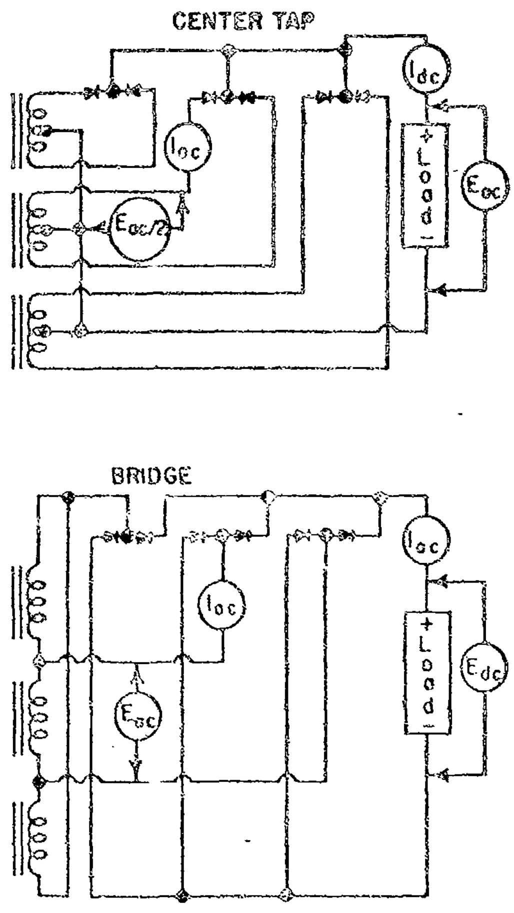


Fig. 1-52. Three-phase full-wave circuits.

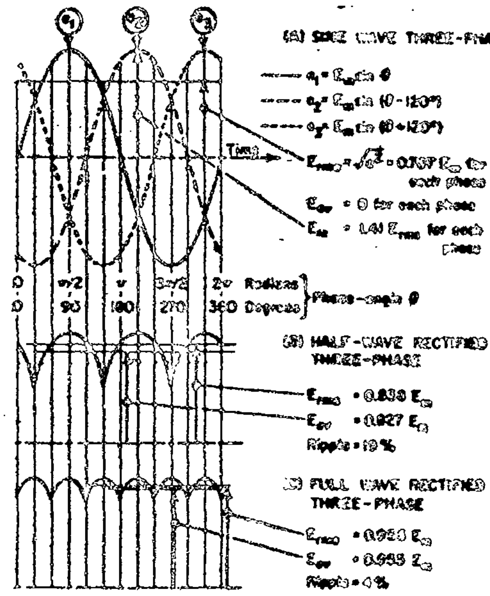


Fig. 1-53. Waveforms in three-phase rectification.

General Recommendations

Putting Into Service. If a new circuit is being tried for the first time, a good procedure is to apply 10 percent of the rated input alternating current and to check all d-c voltages before bringing up the a-c voltage to normal. A variable autotransformer is useful for this preliminary check. It also helps the rectifier if it has not been used recently.

ENVIRONMENTAL EFFECTS

Under normal operating conditions rectifiers will perform as expected with long life and no maintenance. It is conceivable that abnormal environmental conditions will cause trouble. Some of these are seldom encountered, but they may occur. This section applies to external environmental conditions. With temperature, for example, the overloading and consequent overheating of a rectifier is not considered here, but only the external conditions of extra high and extra low temperatures.

Temperature. With very high and very low temperatures, the different expansion rates of the component parts of a rectifier may cause mechanical stresses between the component parts. The maximum allowable temperature depends on the particular design.

Mounting. Do not put the rectifiers under a chassis if it is feasible to put them on top. The extra heat radiation and air circulation will help the rectifier if it is out in the clear.

Note: When a selenium unit fails it will give off a pungent odor (hydrogen selenide) which, although disagreeable, is not dangerous if the room is adequately ventilated.

Cool Spot. Put the rectifier in the coolest spot available. If convection cooling is used, the rectifier should be near the bottom of the enclosure, with the warmer components, such as transformers, above it. The chimney effect will draw air through the stack.

Keep Away From Hot Components. Do not mount rectifiers near components which are hot, such as power transformers or power tubes. Put the rectifiers near capacitors or other components which run relatively cool.

Ventilate. Be sure to allow adequate ventilation. Inside a closed small box the rectifier will not be able to get rid of its heat, and its life and current rating will be limited by the temperature rise.

Solder Quickly. Solder all connections quickly. Use adequate heat, but do not overheat. A too-cold iron, applied long enough to solder will do more damage than a quick touch with a hot iron. Alloy of 63-percent tin and 37-percent lead melts at the lowest temperature of the available tin-lead series, and has a small plastic range. It is ideal for soldering small terminals. To solder short pigtail leads, hold the lead in the jaws of pliers, with pliers toward the stack. This will heat the pliers rather than the stack. Use only rosin flux; do not use acid flux.

Humidity. Low humidity is no problem because rectifiers work best under this condition. High humidity affects the leakage across insulation, and if the moisture penetrates, a change in cell characteristics may occur. It is assumed that the humidity is never 100 percent, which would bring up the problem discussed in "Immersion."

Immersion. For some special uses, particularly with high voltage, rectifiers are immersed in insulating oil. Check with the manufacturer. No damage results from oil immersion; in fact, the rectifier is both cooled and insulated. However, fresh or salt water floods may accidentally surround a rectifier. Fresh clean water is not too harmful if the rectifier is deenergized and adequately protected by paint. Dirty fresh water is harmful, and salt water is worse.

Sealed (selenium) units can withstand immersion. The only point to check then is the external insulation of the terminals. Be sure that all power to the rectifier is off before looking for corrosion and dirt.

Corrosion. Various corrosive agents are often present in the air. One of these is salt spray, which is common to installations on marine equipment. In the laboratory, salt-spray conditions are simulated in tests.

APPLICATION HINTS

Several general application hints for semiconductor rectifiers are given below, followed by some that apply specifically to selenium rectifiers.

Line Voltage. Do not take for granted that the 115-volt line is actually 115 volts. Some localities have poorly regulated systems that may supply up to 130 volts, although this is not usual. Industrial power lines which are 220 or 230 may actually be as high as 265 at co[illegible] part of the day or night. It is important to know the maximum since rectifiers are sensitive to reverse voltages greater than their peak inverse rating. Reverse voltage failure is not a gradual aging effect. The rectifier may puncture or the excessive I^2R heating will cause rapid, or immediate, breakdown.

Reverse Rating. Do not forget to double the reverse rating requirement when capacitors are used. Although the peak of 130 volts is 184 volts, a half-wave rectifier used to charge a capacitor has to withstand 368 volts.

Peak Voltages. Unlike electron tube rectifiers, semiconductor rectifiers have no "warmup" time. Full d-c output voltage is available as soon as the rectifier is connected to an a-c source. If, therefore, the rectifier load does not draw current as soon as it is available, the full no-load voltage will be impressed across the load and also across a filter capacitor. To prevent damage to the equipment from such an occurrence, put in series with the rectifier and the power line, some current limiting device such as a thermistor, which has high cold resistance and low hot resistance.

Polarity. In using electrolytic capacitors, be sure of the polarity. Connecting the capacitor backward will almost certainly damage the rectifier.

Fuse. Single-phase filter circuits using large capacitors may profitably use a fuse in series. This will protect the rectifier in case the capacitor should short circuit. The fuse may be quite large; fuses rated at five times the d-c load current should be adequate.

The following hints are given for the application of selenium rectifiers.

Shelf Life. Rectifiers in active use will retain their ability to block reverse voltage. A rectifier kept unused on the shelf for months, or one used in a cricuit with only forward voltage applied, may lose some of its reverse blocking ability. Such cells may be reformed in minutes by gradually applying their rated voltage. This is preferably done with no d-c load.

Maintenance. A selenium rectifier requires no maintenance. Keep it cool, put it to work. However, the bus-bar bolts should be checked for tightness after a few months of use.

Aging. All selenium rectifiers change with age; their forward resistance increases. This factor varies widely with conditions and with manufacture. Some cells change less than others, but they all change. Actually a 100 percent increase in the forward drop is seldom serious when proper precautions are taken in circuitry. Means must be provided for applying a slightly higher a-c voltage to the rectifier to maintain the specified d-c output voltage.

Mechanical Damage. In bolting on bus bars, be sure that rectifier terminals are not twisted. It is good practice to hold both bolt and nut with separate wrenches, so that no torque is applied to the terminals. Mounting bolts and studs which hold the stack together are correctly set with a torque wrench at the factory. Do not tighten. It is possible to crack the contact between spring washer and selenium, rendering the stack inoperative.

Brackets. On small selenium radio stacks, the mounting brackets may face the rectifier the wrong way; the terminals should perhaps come out at some other angle. In loosening the nut which holds the bracket, be sure to avoid turning the nut holding the end of the stack. This will prevent breaking the paint seal which holds the spring washer securely to the counterelectrode. Once a stack has been painted, it is not possible to change the relative angles of the terminals protruding from the stack.

Do Not Bend the Plates. This especially applies to the large plates in power stacks. Flexing the base plate may crack the selenium or the contact between the spring washer and the counterelectrode. Cracking either of these will damage the rectifier.

Paint Is Not Insulation. Do not depend on the paint coating as an insulator. Space the cells away from conducting members of all kinds.

Flaw Detection. The connections between spring washer and alloy, bolted connections, paint covering spring washers, and selenium plates should all be inspected visually for cracks, flaws, and open connections. Loose bolts are readily detected with a torque wrench. Electrical characteristics should be tested, specifically the forward drop.

Cracked paint usually is serious. Moisture will enter once the spring washer has moved away from the counterelectrode, because the spring washer seldom returns to its original proper place. Minor cracks which do not affect electrical tests can be touched up with paint. Loose bolts are readily tightened.

Environment

Corrosion. Salt spray is the most likely cause of corrosion.

Heavy paint coatings baked on, in several coats, prevent salt-spray damage. The whole metal structure should be properly painted after terminals are connected.

Slight corrosion of the terminals can be washed off with water or carefully brushed away. Then the rectifier can be touched up with proper paint.*

Very high humidity can cause corrosion of bare metal terminals. Corrosion may also occur by a poor paint coverage on selenium rectifier plates. Electrically, the back resistance will decrease below an acceptable value. A ground test will also show insulation leakage.†

Electrical equipment in operation normally runs a few degrees warmer than its surroundings. This reduces the relative humidity and helps the situation. In some cases, the rectifier may be left energized (possibly without d-c load) to keep it warm and dry.

---

*Not all paints are compatible with selenium rectifiers—check with the manufacturer.

†In all cases of electrical tests, the rectifier should first be completely disconnected from its associated electrical circuit.

If a rectifier shows signs of corrosion, it should be cleaned thoroughly.

Brush off corrosion. Check electrical characteristics, reverse currents, and ground test (insulation to ground). Touch up any bare spots on the rectifier plates.

Sand and Dust. The circulation of sand and dust must be considered with fan-cooled rectifier units. On a much smaller scale than sandblasting, forced-air cooling removes surfaces. It is possible that the dust from forced-air cooling may be corrosive.

The leading cell edge of a selenium stack, where air flow hits first, should be carefully inspected. The shiny paint surfaces on the rectifier plates lose their smoothness and show a rough texture. Under severe conditions, the bare metal will show through.

Large particles in the air stream can be trapped with a mechanical filter. Small particles can be eliminated by an electrical precipitation method.

Paint may be touched up where bare spots show or where the surface is badly eroded. Unless corrosion is also present, the electrical tests should show normal.

Vibration and Shock. Vibration is a more or less continuous to-and-fro motion with relatively low amplitude. Shock is a very heavy blow which seldom occurs. Either can damage a rectifier. Vibration at a natural frequency of a stack mechanical structure will build up a resonance condition. Shock is somewhat the same because after a heavy blow, the rectifier vibrates at its natural period (or its several natural periods) of vibration.

The results of vibration and shock are cracked seals between connections and, possibly, other mechanical damage.

Shock or cushion mountings are often desirable in preventing vibration or shock. Some severe cases indicate multiple-stud assemblies should be used rather than the single-stud construction. In general, the aluminum base plate for selenium is better than the alternative use of heavier metal base plates. Selenium rectifiers with a large area contact are better equipped to take vibration and shock than the smaller area silicon and germanium rectifiers.

Air Pressure. As a rule there are small air pockets in selenium rectifier stacks; for example, between the spring contact washer and the counterelectrode. Under severe conditions, such as double normal atmospheric pressure, these air pockets may expand or contract enough to break the paint seal of the washer and counterelectrode. High-voltage rectifiers (of 5000 volts or over) may exhibit corona effects at very low air pressure. Because of the presence of ozone during corona, these effects are similar to corrosion.

Visual inspection may disclose ill effects of air pressure, or a crack in the base plate.

A hermetically-sealed rectifier, designed and tested for the anticipated air-pressure ranges, will not have air-pressure troubles. Another prevention method is to place the rectifier in a container kept near atmospheric pressure (plus or minus 20 percent).

Nuclear Radiations. There are many possible radiations to consider. The comments here are tentative and subject to revision as more information becomes available. Bombarding the rectifying material can cause damage to the electrical properties. It is expected that selenium will be only slightly affected since it is not primarily dependent on a single crystal structure, as are silicon and germanium.

Test data reported 18 February 1957* indicates that selenium rectifiers suffer no permanent damage and are less harmed during radiation than are germanium and silicon rectifiers. The latter units suffered changes in reverse resistance of approximately two orders of magnitude. It should be remembered, however, that the initial reverse resistance of silicon cells is much greater than that of selenium or germanium units.

A standard electrical test should be made of both the forward and reverse characteristics. A detector may be used to indicate severe radioactive effects.

Sunshine. Since a photovoltaic cell can be made of selenium, it is possible that power rectifiers will change characteristics due to sunlight. The resultant increase in leakage is usually negligible.

Fungi. Even in the United States, there are many locations where fungus growth is a

* Air Force Contract AF33(616)-37[illegible].

problem. Fungi grow most readily on organic materials such as insulation, but also grow on paint surfaces and on slightly dirty bare metal surfaces.

Fungicide finishes are standard for equipment used in many parts of the world. The usual rectifier paint (baked on in several coats for salt-spray resistance) is covered by a fungicide varnish. After bare metal terminals are connected, a fungicide varnish may be applied to them also.

There is no satisfactory method of reconditioning once fungus growth has taken place. There may be unseen or undetected damage to the rectifier. It is much safer to replace the unit with a new one. It is possible to remove fungus from connecting bare and cables by mechanical brushing.

BIBLIOGRAPHY

Bendz, W. I., "Electronics for Industry," John Wiley and Sons, Inc., New York, 1947.

Burnstein, F., and P. Egli, "Advances in Electronics and Electron Physics," L. Marton, Ed., Vol. 7, Academic Press Inc., 1955.

Cataldo, J. T., "Versatile Selenium Rectifiers," Electronic Equipment, November 1955.

Dunlap, W. C., "Introduction to Semiconductors," John Wiley and Sons, Inc., New York, 1957.

Gutzwiller, F. W., "Rating and Application of Germanium and Silicon Rectifiers," Communication and Electronics, AIEE, January 1957.

Henisch, H. K., Ed., "Semiconducting Materials," Thornton Butterworth Ltd., London, 1951.

Henkels, Herbert W., "The Fused Silicon Rectifier," Communication and Electronics, AIEE, January 1957.

Henny, Keith, Ed., "Radio Engineering Handbook," 4th Ed., McGraw-Hill Book Co., Inc., New York, 1950.

Hunter, Lloyd P., "Handbook of Semiconductor Electronics," McGraw-Hill Book Co., Inc., New York, 1956.

Jackson, S. P., "Selection and Application of Metallic Rectifiers," McGraw-Hill Book Co., Inc., New York, 1957.

Lee, Reuben, "Electronic Transformers and Circuits," 2nd Ed., John Wiley and Sons, Inc., New York, 1955.

Millman, Jacob, and Samuel Seely, "Electronics," 2nd Ed., McGraw-Hill Book Co., Inc., New York, 1951.

Mott, N. F., and R. W. Gurney, "Electronic Processes in Ionic Crystals," Oxford University Press, New York, 1940.

Parrish, F. W., "Arc Suppression with Semiconductor Devices," Electrical Manufacturing, June 1956.

Pearson, G. L., and W. H. Brattain, "History of Semiconductor Research," Proc. IRE, Vol. 43, No. 12, December 1955.

"Reference Data for Radio Engineers," 4th Ed., Federal Tel. & Radio Co., Clifton, N.J.

Schockley, W., "Electrons and Holes in Semiconductors," Van Nostrand, 1950.

Seitz, F., "The Modern Theory of Solids," McGraw-Hill Book Co., Inc., New York, 1940.

Seitz, F., "The Physics of Metals," McGraw-Hill Book Co., Inc., New York, 1943.

Smith, F. Langford, Ed., "Radio Designer's Handbook," 4th Ed., Radio Corporation of America, Harrison, N. J., 1953.

"Solid State Electronics Issue," Proc. IRE, Vol. 43, No. 12, December 1955.

Storm, H. F., "Magnetic Amplifiers," John Wiley and Sons, Inc., New York, 1955.

"The Radio Amateurs Handbook," 31st Ed., The American Radio Relay League, West Hartford, Conn., 1954.

Torrey, H. C., and C. A. Whitmer, "Crystal Rectifiers," McGraw-Hill Book Co., Inc., New York, 1948.

Wilson, A. H., "Semiconductors and Metals," Cambridge University Press, London, 1939.

Wright, D. A., "Semiconductors," John Wiley and Sons, Inc., New York, 1950.

VIBRATORS*

The vibrator is the nucleus of a power supply that furnishes plate power for mobile electronic equipment. A power supply built around the vibrator eliminates the need for a generator or dynamotor where only moderate amounts of power are needed.

The advantages gained by using such an approach to the mobile power supply problem are good efficiency, small size (vibrator

* For details on vibrators greater than provided in this section, refer to the "Vibrator Guide," P. R. Mallory Co., from which much of this text was compiled.

power supplies can be built into the assemblies they energize), light weight (4 to 6 watts of output power per pound of weight), quiet operation, low cost, provision for different output voltages, small amount of radio interference, ease of replacement, and d-c voltage outputs up to 1600 volts. Disadvantages include poor voltage regulation and the necessity of a low-operating temperature. The absolute maximum temperature is about 85 C and the ambient temperature should not exceed 55 C for long contact life. At low temperatures, the vibrator will tend to warm itself up, and thus vibrator life is not affected.

The basic elements of the vibrator are an electromagnetic coil and an armature that carries a set of contacts (see Fig. 1-54). Application of the proper drive voltage creates an electromagnetic field that causes the armature to swing in one direction to contact

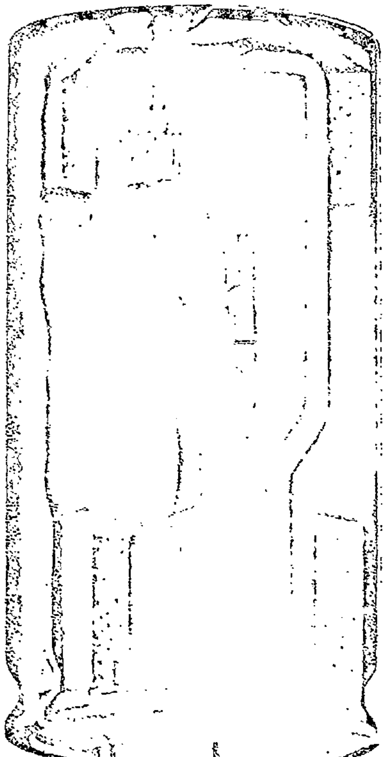


Fig. 1-54. Vibrators are modest in size and weight, may be sealed, permit plug-in installation. (P. R. Mallory & Co., Inc.)

one of a fixed pair of contacts. In one conventional circuit, this motion opens a set of contacts in series with the drive coil permitting the electromagnetic field to collapse. Spring loading pulls the armature in the opposite direction and carries it to the point where it closes on the second fixed contact. This action continues in cyclic fashion as long as the drive voltage is applied. The frequency of operation is a compound function of the armature mass and traverse, spring tension, and electromagnetic flux density.

The make and break action of the contacts interrupts the application of power to the primary of a step-up transformer. The varying flux linkage, which results from this cyclic interruption of power, induces a secondary winding voltage of a magnitude set by the transformer turns ratio. Rectification of this high voltage alternating current makes available direct current for plate operation of vacuum tube stages.

The principal use of vibrators is in automobile radio receivers and other mobile communications equipment, both in civilian and military applications. Vibrators are used in other applications such as signaling equipment, ultraviolet prospecting lamps, and Geiger counters. The vibrator, within its power ratings, has proved to be a satisfactory way of obtaining high-voltage direct current from low voltage direct current for hundreds of various requirements in the electrical equipment field.

Vibrators deliver optimum performance when employed with properly designed transformers, properly selected buffer capacitors, and other circuit components of the power-supply system.

TYPES OF VIBRATORS

Single Interrupter

The most universally used vibrator circuit is the simple full-wave interrupter illustrated in Fig. 1-55. This unit functions essentially as an electrically-driven single-pole double-throw switch, causing current from the battery to flow first in one half and then in the other half of the center-tapped transformer primary. The frequency of the alternating voltage induced in the secondary is determined by the rate of primary circuit interruption. This secondary voltage may be rectified and filtered in a conventional manner to supply a high-voltage d-c output. The buffer capacitor serves to minimize the buildup of

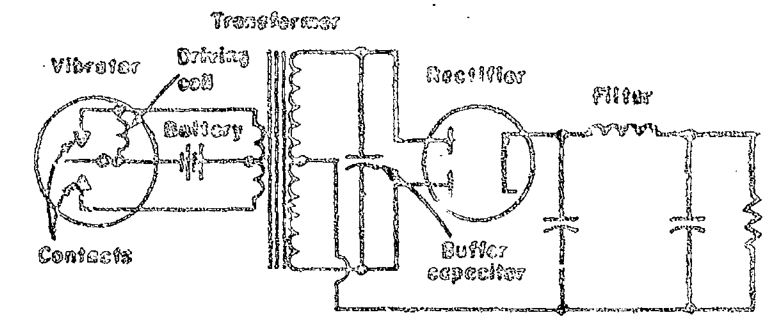


Fig. 1-55. Single-interrupter vibrator with transformer, rectifier, and filter.

transient inductive voltages with resultant sparking across the interrupter contacts by tuning the secondary circuit to provide a load that appears more nearly resistive to the primary. The single-interrupter vibrator is commonly referred to as a nonsynchronous vibrator.

Dual Interrupter

The dual interrupter is used where heavy load-handling capabilities and long service life are needed. Two sets of contacts, shown in Fig. 1-56, are used to energize two separate primaries of a special vibrator transformer. The advantage of the dual interrupter lies in splitting the primary current required to be carried by a single set of contacts, reducing arcing and extending service life.

Synchronous Rectifier

The synchronous rectifier is a single vibrator that accomplishes the dual function of interrupting the primary d-c voltage and rectifying the secondary a-c voltage (see Fig. 1-57). Essentially, the synchronous rectifier operates as a double-pole double-throw switch. Used in conjunction with a suitable transformer and low-pass filter, it forms a complete power pack for mobile applications. In using the synchronous rectifier, one side of the secondary high-voltage circuit must be common with one side of the battery. In addition, the polarity of the high voltage will be determined for a given transformer connection by the polarity of the battery. Care must be taken to observe the polarity of the battery and the marking on the synchronous vibrator when making an installation.

Reversible Synchronous Rectifier

This is simply the synchronous rectifier wired in such a manner that the desired high-voltage output polarity may be obtained regardless of which pole of the battery is grounded. As shown in Fig. 1-58, the vibrator may be installed in either of two positions, permitting either positive or negative output without altering the existing battery ground polarity.

Split-Reed Synchronous Rectifier

Use of the split-reed synchronous rectifier (see Fig. 1-59) permits elimination of the common connection between the high-voltage winding and the source voltage battery. The primary and secondary circuits utilize individual reed segments, electrically insulated from each other but mechanically connected.

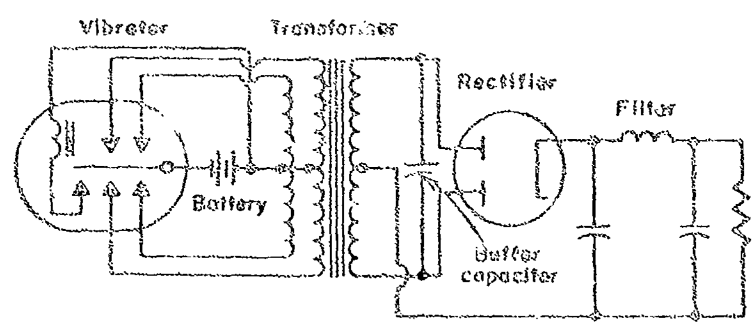


Fig. 1-56. Dual interrupter with transformer, rectifier, and filter.

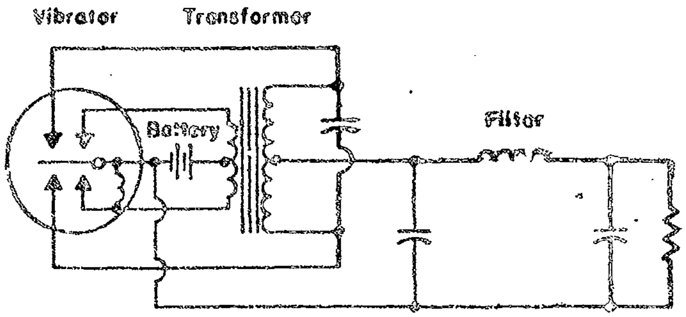


Fig. 1-57. Synchronous rectifier vibrator with associated circuitry.

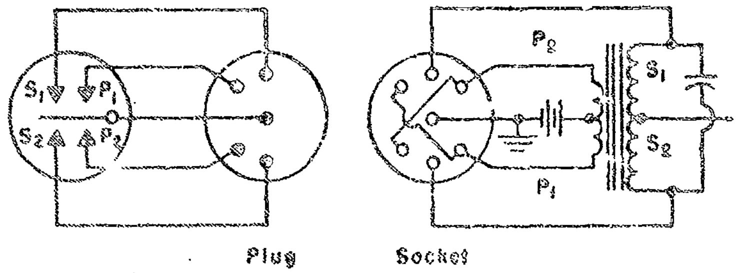


Fig. 1-58. Orientation of the vibrator in its socket controls the output polarity obtained from the power supply.

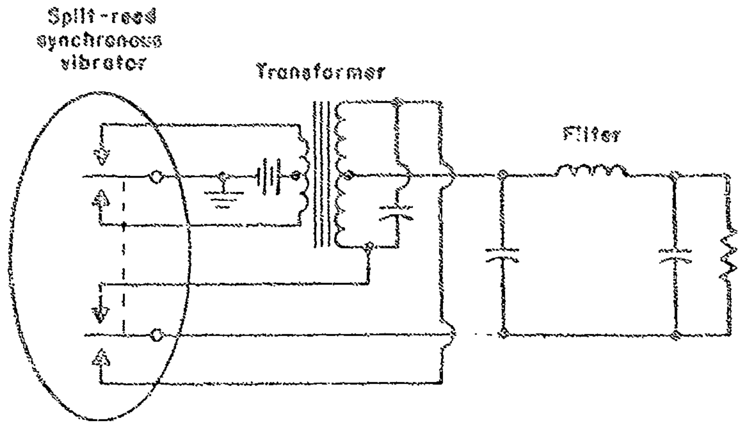


Fig. 1-59. Split-reed synchronous rectifier.

The interrupter action is that of a double-pole double-throw switch without common electrical connections. This circuitry permits tapping off below-ground potentials for bias purposes.

Driving Circuits

Two methods of connecting a vibrator drive coil have been accepted by the industry. There are basic advantages to both types and they are used in about equal quantities.

Shunt-Coil Connection. In the shunt-drive circuit, as shown in Fig. 1-60(A), the coil is connected across the armature and one contact, and the contacts are normally open. When voltage is applied to the circuit, current flows from the battery through one-half of the transformer primary, the driving coil, and back to the battery. The field of the driving coil pulls the armature to the [illegible] until the contacts close, which short circuits the driving coil and permits a much larger current to flow through the left half of the trans-

former primary. The momentum acquired by the armature causes it to swing past the position of contact closure, carrying the fixed contact along with it on its spring. Since the driving coil is now short circuited, there is no force tending to hold the reed to the left; it springs back, opening the contacts on the way and then closing the other pair of contacts. This closure permits a heavy current to flow through the right half of the primary, which more than balances the weak current in the left half, and the second half of the output wave is started. The armature continues to swing to the right past the point of closure of the right contact pair, then reverses, and starts a new cycle. The frequency of vibration is determined principally by the material and construction of the armature.

The shunt drive has the disadvantage of allowing the driving-coil current to flow through one-half of the transformer primary while the load current flows through the other half, which results in an asymmetrical voltage wave. This type of vibrator is used extensively in automobile radio power supplies because of its low cost.

Series-Coil Connection. In the series-drive circuit, the driving coil is connected directly across the d-c supply in series with an extra pair of normally closed contacts. The action is exactly that of the conventional doorbell. Energizing the coil pulls the series contacts apart and breaks the coil current; whereupon the armature springs back, the contacts reclose, and the cycle repeats. The series-drive circuit is shown in Fig. 1-60(B). Its principal disadvantage is the slightly greater cost of the additional pair of contacts, but the separation of the driving and load currents and the greater ease of adjustment make it decidedly preferable to the shunt-drive type of vibrator.

Mounting Methods

Vibrators are usually packaged in cylindrical metal cans with contact pins at one end to permit plug-in installation and removal. Some vibrator bases fit standard 8-pin octal or 7-pin miniature tube sockets. Several types require special sockets that are usually fitted with spring clips that snap into embossed grooves in the can when the vibrator unit is plugged in. In either case, adequate means for holding the unit in the socket is required to prevent it from working loose because of its own vibration or because of external shocks.

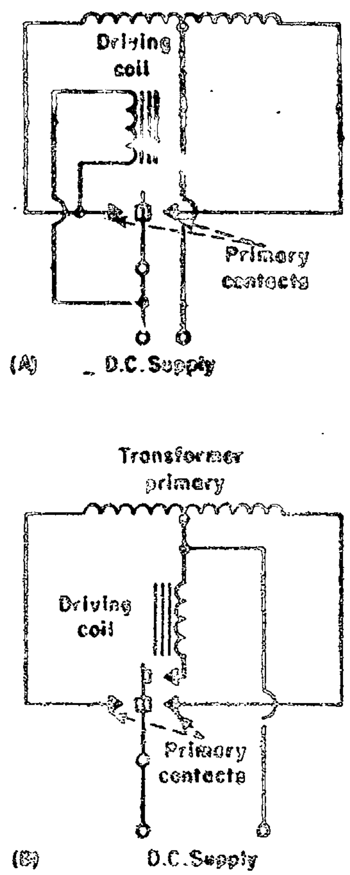


Fig. 1-60. (A) Shunt-drive circuit. (B) Series-drive circuit.

The can is lined with a resilient sheath of sponge rubber and the connections from the vibrator to the base pins are made with flexible wire so that the vibrator is mechanically isolated from the can and the chassis. The can is so designed that its natural vibration frequency is remote from that of the vibrator. Many vibrator cans merely provide mechanical and dust protection for the vibrator, but hermetically sealed types are available for use at high altitudes and in unfavorable climates. Vibrator units may be mounted in any position.

Large vibrators are usually mounted in rectangular metal cans that are often provided with two tube bases on the bottom of the can. The use of two bases, separated by a few inches, provides a much more rigid support than can be obtained from a single base. The vibrator is usually isolated from the can by rubber shock mounts. The cans may or may not be hermetically sealed and may be mounted in any position.

Life Expectancy

The life expectancy of a vibrator is generally the life of its contacts. The contacts are mounted on flat steel springs that allow them to yield against impact and to help eliminate bouncing. Contact bouncing is highly undesirable because it results in inefficient operation and greatly shortens the life of the contacts. Contacts may fail either by burning or by mechanical wear. Ionization of the contact metal leads to pitting and, eventually, to the generation of heat sufficient to weld the contacts together.

The slight sliding of one contact over the other, which results from the resilience of the spring, helps to keep the contact surfaces clean; however, if this movement is too great it will result in excessive wear and short contact life.

In an emergency, a vibrator that has failed because the contact spacing has been excessively changed by burning or wear may be repaired by replacing the contacts and dressing the surfaces smooth.

Interference

The vibrator functions to make and break the application of direct current to an inductive load. The waveforms of the resulting voltages and currents are more nearly rectangular than sinusoidal. These waveforms are very rich in harmonics and are capable of producing a large amount of radio interference. The vibrator manufacturer provides internal shielding between elements within the vibrator can to minimize undesired coupling of signals by electrostatic and electromagnetic means. It is up to the equipment design engineer to devise means for preventing interference that originates within the vibrator from jeopardizing operation of circuits external to the vibrator. This means shielding and filtering leads into and out of the vibrator to prevent coupling harmonic components from the cycling contacts, through the leads, to other stages in an equipment. Most frequently, the source voltage receives a superimposed voltage component at the vibrator make-break rate that is carried to all parts of the equipment using this supply voltage. Frequently, this primary power line must be given special treatment to isolate it from such undesired signal components.

Comparable Devices

The vibrator power supply is preferred over the dynamotor and the transistorized power supply where initial cost is a required consideration (see Table 1-9). It is superior to the dynamotor from the maintenance standpoint, although it is inferior in this respect to the transistor power supply.

Under adverse climatic conditions, the vibrator power supply is superior to the dynamotor, which is inherently susceptible to contamination by salt spray and dust-laden environments that attack its commutator and brushes. Sparking at the brushes makes the dynamotor too hazardous to be used in explosive or volatile atmospheres.

The electrical efficiency of the vibrator power supply (40 to 75 percent) is appreciably higher than that of the dynamotor (35 to 65 percent). The vibrator power supply, however, is inferior to the transistorized power supply in this respect. The vibrator power supply cannot achieve the voltage regulation of the dynamotor, which is preferred in applications requiring low-voltage and high-current outputs. Dynamotors are excessively heavy, and their use in airborne applications generally involves a costly compromise in terms of weight accumulation. Dynamotors do not require as much low-frequency filtering as do vibrator power supplies, but they create a form of radio interference that is usually much harder to eliminate than the hash of the vibrator.

Advantages

The vibrator power supply possesses the advantages of being a compact and inexpensive means of obtaining moderate quantities of power from a storage battery. One of its excellent features lies in the comparative ease with which it can be made to supply several different outputs simultaneously. One such commercially available supply delivers, all at the same time, 5 ma of direct current at 2500 volts for a cathode-ray tube, 5 ma at 150 volts for bias, and 100 ma at 250 volts for plate supply. The whole unit weighs 8 to 9 pounds and operates from a 6- to 24-volt battery supply with an efficiency of 50 to 60 percent. Another advantage is that since a vibrator supply is composed of a number of small, mechanically independent units, it can be built into the same assembly to which it supplies power.

Disadvantages

The prime disadvantage of the vibrator power supply lies in the difficulty of regulating the output voltage except by the use of

Table 1-9—Comparison of DC-to-DC Conversion Systems

Characteristic	Transistorized power supply	Vibrator power supply	Dynamotor
Power range (watts)	10-1000	3-500	5-500
Efficiency (%)	75-90	40-75	35-65
Regulation (%)	Normal, 5-10; with regulation, <1	20-25	5-10
Input voltage (volts)	1.5-32	1.5-115	6-115
Max output (kv)	1.6	1.6	1.5
Max No. of outputs	Unlimited	Unlimited	3
Storage ambient (temperature deg C)	-55 to +95 (at mounting plate)	-55 to +125	-55 to +125
Operating ambient (temperature deg C)	-55 to +75	-55 to +125	-55 to +125
Operating life	Excellent	Poor (25-1000 hours)	Good with maintenance (25-3000 hours)
Watts per pound	30	8	12
Cubic inches per watt	<1	3	1.5
Overload protection	Can be built in	Required	Required
Operating maintenance	None	Periodic vibrator replacement	Periodic service required
Storage maintenance	None	None	Periodic service required
Radio interference	Negligible	Yes	Yes
High altitude operation	Sealed	Sealed	Sparking
High humidity effects	Sealed	Sealed	Susceptible to corrosion
High shock, vibration, acceleration	Negligible due to no moving parts	Contact assembly susceptible to damage and erratic performance	Brush bounce, armature susceptible to damage

comparatively inefficient series-tube regulators in the output leads. Power consumption is increased in heating the cathodes of rectifier and regulator tubes; this power is usually supplied by the vibrator transformer. The useful life of the vibrator itself ends with the end of contact life.

Power Capabilities

In terms of power output, vibrators are generally divided into two classes. Small vibrators of the automobile radio class usually have a single pair of input power-handling contacts and can handle powers up to about 50 watts. Power up to several hundred watts (400 watts continuous duty, 600 watts intermittent duty) can be supplied by the so-called power vibrators, which usually have several pairs of contacts. The input current must be divided equally between the several pairs of contacts, either by accurate contact setting, by equalizing resistors or chokes, or by multiple transformer primaries with a separate pair of contacts feeding each primary. The method using no equalizing resistors gives the best rectification or a-c output. Cold-cathode gas-tube rectifier tubes are particularly suitable for use with vibrators and require no heater power.

Power-to-Weight Ratio

The weight of a vibrator power supply varies between wide limits, depending upon the required output, number of outputs, degree and type of filtering, method of packaging, and so forth. Outputs of from 4 to 6 watts per pound can be expected from usual types of units. A moderate increase in design frequency makes possible a saving of weight through physical reduction in the required transformer size and also by simplification of the filtering problem.

Voltage Regulation

The voltage regulation of a vibrator power supply is approximately 20 to 25 percent for a-c output and 15 to 20 percent for a-c output.

Contact Frequency

The frequency of most vibrators is set between 100 and 125 cps, but there is a trend toward higher frequencies. Several types of vibrators operate at 180 cps, which permits a weight saving in the transformer and filter of about 25 percent. Vibrators are also manufactured for operation at 400 cps; but because of the difficulty of obtaining clean contact make and break at this frequency, contact life is currently less than satisfactory for most applications.

OPERATING PARAMETERS

Most effective application of vibrators is obtained when proper allowance is made for their unusual properties. Some of these properties are discussed in the following paragraphs.

Time Closure Factor

The time closure or time efficiency is the ratio of the time the contacts are closed during the interval of one complete cycle to the total time of one complete cycle. It is usually expressed as a decimal or percentage. This value varies with different manufacturers, with selected design frequencies, and with aging of the vibrator. For highest efficiency and best results, it should be kept as large as possible. Present-day vibrators have a time efficiency of 0.75 to 0.95. The values used in calculating time efficiency as a function of total cycle interval are illustrated in Fig. 1-61. The intervals T_1 and T_3 are referred to as the on times; intervals T_2 and T_4 are called off times. The formula for vibrator time efficiency is

$$W_t = \frac{T_1 + T_3}{T_1 + T_2 + T_3 + T_4}$$

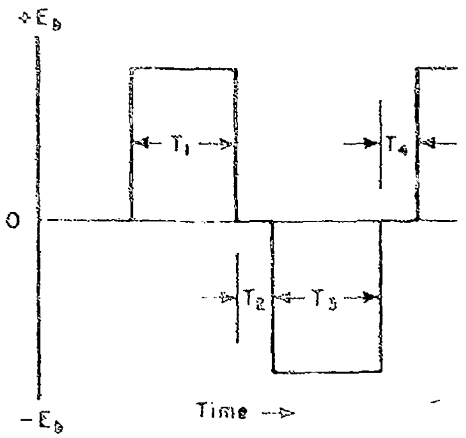


Fig. 1-61. Oscillogram illustrating the values used in calculating time efficiency of a vibrator.

Timing Capacitance

The timing or buffer capacitance in a vibrator power supply functions to increase vibrator contact life and prevent the generation of dangerously high transient potentials that might cause breakdown of transformer insulation.

In a vibrator power supply, the vibrator contacts make and break the connection of an inductive load to the d-c supply. Unhindered, the induced secondary voltage, rich in harmonics, can assume a magnitude that will break down the transformer insulation and cause severe arcing at the vibrator contacts. To control these high induced voltages, it is necessary to connect a capacitor of proper value across one of the transformer windings. This capacitance combines with the effective inductance of the transformer winding to form a tuned circuit that is set in shock oscillation at each opening of the contacts. By properly selecting the value of capacitance to match the transformer and vibrator characteristics, the resulting oscillation can be made to perform the useful function of reversing the induced voltage, making it coincide with the voltage applied to the transformer by the closing of the vibrator contacts on the succeeding half cycle. The value of this timing capacitance is very critical and must be selected with particular care in regard to both the circuit and the vibrator mechanism.

The value of capacitance required is inversely proportional to the square of the voltage and depends upon the core material characteristics, the vibrator frequency, and the contact-closure factor. For low input voltages, a large value of capacitance is needed. Placing the capacitance in the secondary circuit permits a reduction in value because of the higher voltages encountered. To achieve a practical-sized capacitor, electrolytics must be used; but since this type of capacitor has adverse temperature characteristics, its use imposes voltage and temperature limitations. A capacitance close to the value to give the correct frequency of oscillation for 100 percent closure is given by

$$C_o = \frac{HL_m(1-W_t) \times 10^6}{8N_p fE}\left(\frac{N_p}{N_s}\right)^2$$

where L_m = length of magnetic path in inches

H = the value given by the BH curves for the transformer being used at the value of B corresponding to the voltage E

W_t = vibrator time efficiency

E = highest battery voltage*

If the capacitor is to be placed across the primary, then

$$C_p = C_s\left(\frac{N_s}{N_p}\right)^2$$

Variation with Age

Vibrator frequency decreases with age. The contact-closure factor or timing efficiency also decreases because of contact wear. Proper compensation requires that the timing capacitor value be increased somewhat above the value needed for a new vibrator.

As the vibrator contacts wear, spikes will appear superimposed on the voltage output wave. These spikes represent high harmonic transient voltages that are added to the high output voltage during no-load conditions. The resulting peak voltage may puncture the capacitor insulation unless the selected voltage rating incorporates a safety factor.

12-Volt Circuits

In designing circuits for use with 12-volt or higher power sources, a phenomenon is encountered that is not prevalent in 6-volt circuits. It is referred to as starting flare and is capable of destroying vibrator contacts very rapidly. Starting flare results from saturation of the vibrator transformer on the start cycle, which causes an abnormally high primary current to be drawn. The resulting arc across the contacts is extremely hot and highly destructive. Several methods exist for overcoming this initial action. The most practical of these is to design the transformer with sufficient inductance in the primary circuit and to use a buffer or timing capacitor to insure reliable starting. It is also common practice to utilize an additional capacitor in the secondary circuit to provide the proper timing for the vibrator. The primary buffer capacitor is selected to meet the starting requirements; the capacitor in the secondary circuit serves to time the vibrator circuit. A variety of circuits currently used, and incorporating buffer capacitors in transformer secondary circuits, is shown in Fig. 1-62.

*Application Design Note, ADN-95, 31 October 1955.

SELECTION FACTORS

Selection of the proper vibrator to be used in designing a circuit requires a comparative evaluation of the commonly available vibrator types that will most efficiently accommodate the dynamic load conditions to be expected. Selection of a vibrator should incorporate a suitable safety factor. The choice between an interrupter and a self-rectifying vibrator should be made according to the types of service desired, the operating efficiency necessary, and the limitations of the various vibrator mechanisms themselves. The selection of a commercially available vibrator is strongly recommended to take advantage of the extensive environmental and reliability testing such production units receive and to simplify ultimate replacement of the vibrator unit. The use of special vibrators designed for unusual applications should be avoided. Such vibrators are not readily available from common sources and, in some cases, the special features may involve a compromise of overall operating efficiency.

The following items should be considered in the selection of a vibrator for any circuit application.

Input Voltage

Vibrators are normally rated at input voltages of 4, 6, 12, 24, 32, 110, or 220 volts dc. Circuit design should be aimed at accommodating one of these conventional operating voltages. It should be noted that such specific voltages are nominal values and that associated with each are a higher and lower voltage at which the vibrator will continue to operate satisfactorily. For example, a 6-volt vibrator should exhibit normal operation when driven by an input voltage ranging from 5.0 to 8.0 volts dc. Specific values are given in MIL-V-95A for the 6-volt and 24-volt vibrator types that require normal operation over the ranges 5.0 to 8.0 and 16.0 to 30.0 volts dc, respectively.

While it is possible to use one vibrator for two adjoining input voltage ratings by use of appropriate resistors, the designer should not attempt to utilize one vibrator for more than two such voltages. Instances have been encountered where a vibrator was used to operate periodically on any one of three different input voltages. In all cases, operation and reliability were unsatisfactory.

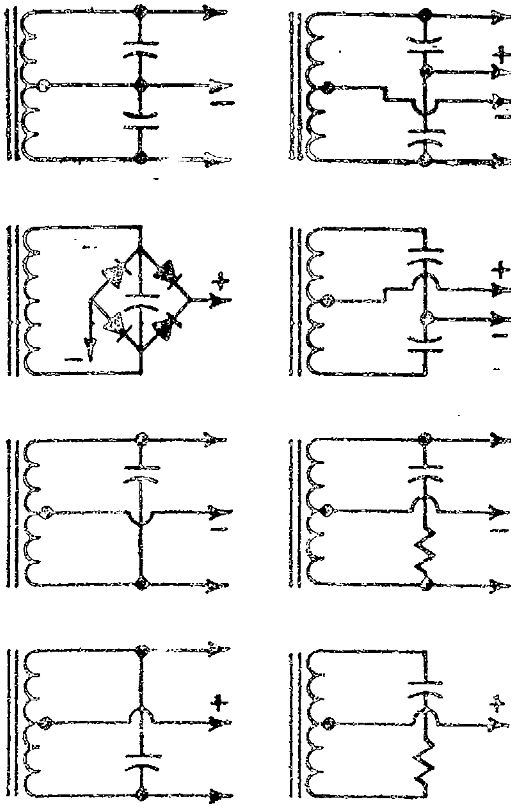


Fig. 1-62. Buffer capacitor circuits commonly used with transformer secondary windings. (American Television and Radio Co.)

Current Rating

The input current rating of a vibrator is reduced as the input voltage is increased, and a vibrator can be expected to handle much less current at 24 volts input than at 6 volts. In judging the input current handling ability of a vibrator, the manufacturer's ratings should be consulted. The input current and voltages of some representative vibrator power supplies are listed in Table 1-10. The electrical ratings listed illustrate the characteristics available in vibrators and the selection of output power levels provided by commercially packaged vibrator supplies.

Vibrator Frequency

The conventional operating frequency of vibrators is 115 ±7 cps. The designer should use a vibrator of this frequency range whenever possible. While special frequencies have been used, such departure from the conventional frequency range is usually intended to serve other objectives, such as weight reduction in airborne equipment or to accommodate limitations in the selection of other components. Such departure from the normal frequency range also reduces sharply the number of sources available for replacement units.

Temperature Ranges

Commercially available vibrators will give satisfactory performance over a range of temperatures from -55 to 85 C (-67 to 185 F). The use of vibrators beyond this temperature range will result in substantial compromise of reliability.

Sockets and Enclosures

Vibrators are supplied in a variety of base arrangements and enclosure sizes. Vibrator leads are brought out to pig-tail leads in some units; but an advantage in terms of functional circuit flexibility is achieved by terminating the vibrator elements in socket pins, which permit plug-in installation, removal, and replacement. Several typical basing configurations are shown in Fig. 1-63. All circuit elements are shown except the driving coil, since this is not normally included in a display of basing arrangements. Most commercial vibrators are concentrated in these types, which are designed to suit the prime range of application needs. To facilitate procurement, the design engineer should keep these standardized items in mind.

Output Voltage

It should be borne in mind that the output voltage of any vibrator power supply is a function of the time efficiency of the vibrator, the turns ratio of the vibrator transformer, and the load, together with the efficiency of the rectification means. The vibrators of various manufacturers will vary in time efficiency, depending upon the mechanical constants of the devices. The design engineer should take meticulous care in seeing that representative vibrators from all potential sources are checked in his circuit and should keep in mind that a specific vibrator design to overcome a circuit deficiency generally results in impaired and unsatisfactory performance.

Altitude

All vibrators of current manufacture are intended for use at altitudes up to 10,000 feet.

Table 1-10—Electrical Ratings, Typical Vibrator Power Supplies

(A) 110-Volt A-C Output Type

Input		Output voltage (volts, ac)	Power output (watts)	
Voltage (volts, dc)	Current (amp)		Continuous	Intermittent
6	5	110	20	30
6	7	110	30	40
6	10	110	40	50
6	15	110	60	60
6	20	110	80	100
6	25	110	100	125
6	35	110	150	175
6	20	110	80	100
6	35	110	150	175
12	2-1/2	110	20	20
12	5	110	40	50
12	7-1/2	110	60	80
12	10	110	80	100
12	12-1/2	110	100	125
12	20	110	150	175
12	25	110	200	250
12	12-1/2	110	100	125
12	25	110	200	250
28	4	110	80	100
28	5	110	100	125
28	7-1/2	110	150	175
28	10	110	200	250
32	3-1/2	110	60	100
32	5	110	125	150
32	7-1/2	110	180	200
32	10	110	225	275
110	0.5	110	50	60
110	0.8	110	70	90
110	1.1	110	100	100
110	1.7	110	150	200
110	2.8	110	250	325
110	4.0	110	350	450
110	4.5	110	400	600
110	1.7	110	150	200
110	4.5	110	400	500
220	0.85	110	150	[illegible]
220	1.4	110	250	[illegible]
220	2.3	110	400	600

(B) High Voltage D-C Output Type

Input		Output	
Voltage (volts, dc)	Current (amp)	Voltage (volts, dc)	Current (ma)
6	8	300	100
6/12	16/8	300	200
12	4	300	100
6/12	30/15	500	225

These same vibrators may be used at any altitude when local pressurization is used to maintain an atmospheric pressure range comparable to that encountered between sea level and 10,000 feet. The restriction on altitude applications is derived from the fact that the vibrator is sealed at sea-level atmospheres and, when operated in reduced atmospheres, will be subjected to a differential of pressures tending to pull the case apart.

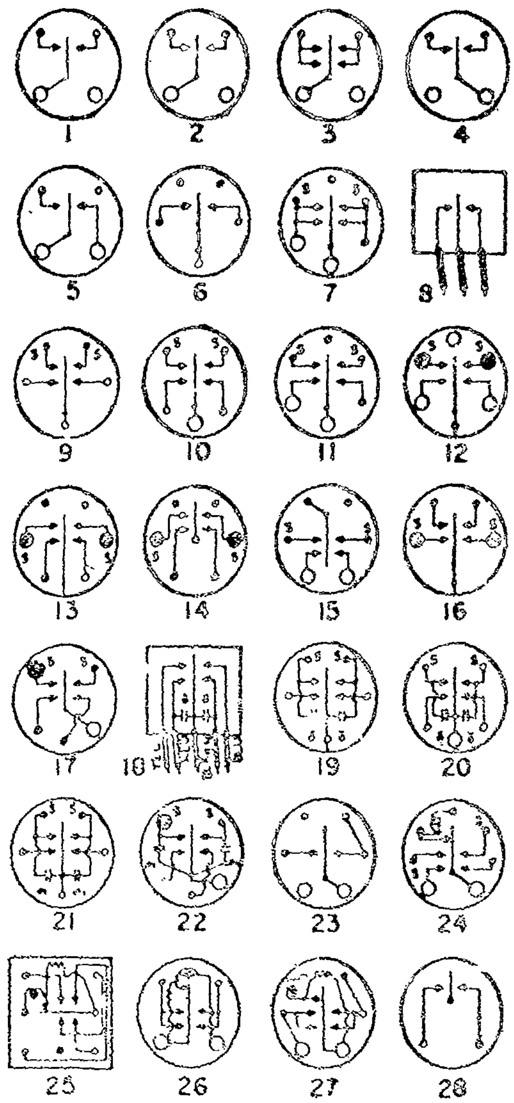


Fig. 1-63. Typical vibrator basing diagrams. Items (8) and (18) feature pig-tail leads; (25) terminates in solder lugs. All others have socket pins for plug-in installation and removal

MILITARY SPECIFICATIONS

MIL-V-95A, 16 September 1955, Vibrators, Interrupter and Self-Rectifying

This specification covers interrupter and self-rectifying vibrators, designed to operate from a d-c source, for use in electronic equipment. This is a general specification, but it also provides valuable information concerning the minimum performance values required of vibrators intended for use in military equipment. Operation at 6 or 24 volts only is covered.

The limitations in design and construction are outlined and the materials permissible are tabulated. Complete test procedures are described that cover dielectric strength, starting voltage, dynamic load, moisture resistance, temperature cycling, vibration, and life aging.

Dielectric Strength. For 6- and 24-volt types, vibrators must withstand without damage, arcing, or breakdown, potentials as shown in Table 1-11. The applied voltage shall be of commercial-line frequency. This voltage must not be applied across the driving coil.

Electrical Rating. The pertinent electrical rating values for the 6-volt vibrator are shown in Table 1-12.

Seal. Vibrators shall be immersed in any suitable bath maintained at 80 to 85 C for a period of at least one minute. An alternate method of test may be used to determine satisfactory sealing, provided the method is proved to be equivalent to that specified herein. Care should be taken not to mistake bubbles caused by entrapped air around pins for bubbles coming from the can. Any vibrator that shows

Table 1-11—Dielectric Test Voltage (RMS), MIL-V-95A

From pin	To can connected to pins	Volts
1	2,5	500
2	1,6,7	500
5	1,6,7	500
6	2,5	500
7	2,5	500

Table 1-12—Electrical Rating, MIL-V-95A

Frequency	115 ± 7 cps
Rated input voltage	6.3 vdc
Max input current at rated input voltage	4.1 adc
Max input voltage	8.0 vdc
Min input voltage	5.0 vdc
Duty cycle	Continuous
Life expectancy	500 hr

evidence of leakage may be given remedial treatment provided evidence is submitted that such remedial treatment is adequate.

Temperature Cycling. Vibrators are required to be subjected to the temperature cycle of Table 1-13 for a total of five cycles performed continuously. The vibrators shall be held at each temperature for sufficient time to allow all parts to reach thermal stability. Vibrators shall then immediately be placed in a suitable test circuit and energized. They shall then be evaluated for normal operation.

Moisture Resistance. Vibrators shall be tested in accordance with Method 106 of Standard MIL-STD-202.

Vibration. Vibrators shall be tested in accordance with Method 201 of Standard MIL-STD-202.

Shock. Vibrators shall be tested in accordance with Method 202 of Standard MIL-STD-202.

BIBLIOGRAPHY

Blackburn, J. F., "Components Handbook," Vol. 17, Radiation Laboratory Series, McGraw-Hill Book Co., Inc., New York, 1949.

"Vibrator Guide," P. R. Mallory Co., Indianapolis, Ind., 1957.

DYNAMOMETERS

The dynamotor combines an electric motor and a generator in one unit, the input power coming from 6- to 28-volt batteries. Some dynamotors have an auxiliary a-c output. The d-c voltage outputs range from 6.3 volts for tube heaters or filaments to several hundred volts for plate circuits. A typical dynamotor is shown in Fig. 1-64.

OPERATING PRINCIPLES*

The construction is such that both the motor and generator sections use the same field,

Table 1-13.—Temperature Cycle for Acceptance Tests

Step	Temperature (deg C)
1	85^{+10}_{-0}
2	25^{+10}_{-5}
3	-55^{+0}_{-5}
4	25^{+10}_{-5}

which is usually energized by the primary power source. The armature windings for both the input and output sections, although electrically independent, are wound in the same core slots. The motor (input or primary) section provides mechanical drive for the armature. The generator (output or secondary) section generates voltage as its armature winding turns pass through the magnetic field and cut the flux lines. The basic arrangement of a dynamotor is shown in Fig. 1-65.

Output Voltage

In many respects, the operation of a dynamotor is similar to that of a motor generator. The output of a motor generator, however, can be varied by control of the generator field. The dynamotor uses a common field so that the output cannot be controlled in this manner. The ratio of the output to input voltages of a dynamotor is fixed.

If a constant input voltage is applied to a dynamotor, the field strength will be practically constant, and the armature will rotate at a speed so as to generate a back emf in the motor winding about equal to the input voltage less the IR drop. The ratio of the output voltage to the input voltage can be reasonably

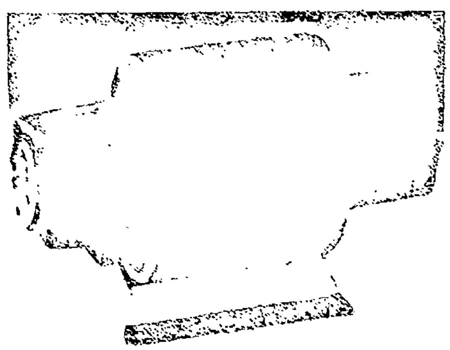


Fig. 1-64. A four-commutator dynamotor with end covers removed.

* Portions of this text and Figs. 1-65, 1-66, 1-67, and 1-68 are from "Direct-Current Machinery," C. S. Siskind, McGraw-Hill Book Co., Inc., 1952.

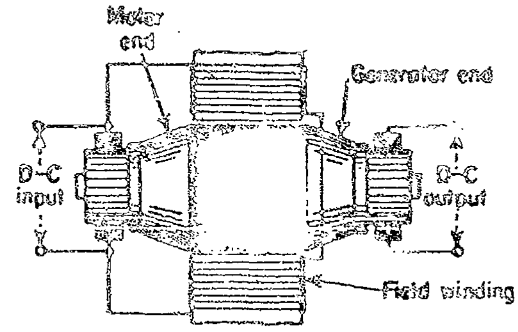


Fig. 1-65. Basic arrangement of a single input and output dynamotor.

represented by the ratio of the two induced voltages, the output voltage and the back emf. Since the armature motor and generator windings are rotating on the same armature at the same rpm in the same field, the ratio of the output voltage to the input voltage is a constant equal to the ratio of effective turns in generator and motor windings.

Variations in load current cause the armature output windings to generate varying torques resisting rotation. The input armature windings compensate for this torque variation by drawing more or less current so as to maintain an rpm to give constant back emf. Disregarding IR drops, the voltages remain the same.

A drop in input voltage causes a drop in field strength and in back emf requirement. Usually a slight drop in rpm results. As a consequence of the lowered field strength, the output voltage drops. Thus, for practical purposes, the output and input voltages are related by a transformation ratio fixed at the time of manufacture.

Voltage Regulation

Voltage regulation of a dynamotor as a function of load ranges from 5 to 20 percent. It is a function of copper losses and the speed-load characteristic of the motor section. As the load rises from zero to the rated maximum, increasing secondary currents cause proportionately larger IR drops. Dynamotors with shunt-wound fields exhibit little speed variation from no-load to full-load, while series-wound fields let the armature rotate at a speed which is approximately an inverse function of load. The speed characteristics of dynamotors with compound-wound fields will range between series- and shunt-wound fields, depending on the degree of compounding. Figure 1-66 shows the relationship between speed and load for the three types of field windings. (1)

The speed regulation of these windings is determined by the amount of torque produced. As in any motor, the developed torque is a function of the field flux density and the current in the input armature windings. Figure 1-67 shows the relationship between torque and armature current for the three types of field windings, and Fig. 1-68 shows the speed vs. torque characteristics. Series field windings are not used alone in dynamotors because of the possibility of runaway under no-load conditions.

Ripple Voltage

Ripple voltage is generally 1 to 1-1/2 percent of the output voltage. The major causes of ripple are:

1. Modulation of the input voltage to the field windings by the input commutator. Ripple frequency is speed (rps) times one half the number of segments in the input commutator.

2. Nonuniformity of the permeability of the magnetic circuit. Ripple frequency is equal to the rps speed.

3. Distortion of the flux pattern because of the armature slot structure. Ripple frequency

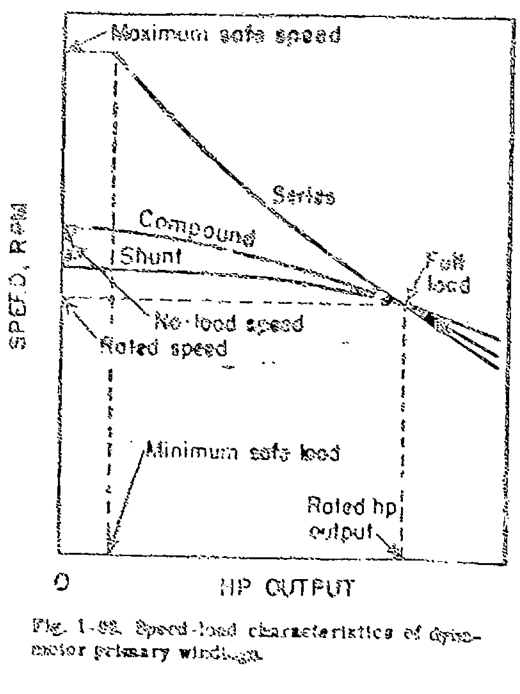


Fig. 1-66. Speed-load characteristics of dynamotor primary windings.

is rps times the number of slots in the armature.

4. Modulation of the output voltage by the output commutator. The frequency is rps times one half the number of segments in the output commutator.

Efficiency

The dynamotor is usually more efficient than comparably rated motor-generator set for these reasons: (1) the dynamotor, having only one armature, has lower mechanical losses, (2) it has only one field loss, and (3) it has superior commutation due to compensating countermagnetic fields produced by the input and output windings.

For a given output power rating, the dynamotor weighs less and occupies less space (volume) than its motor-generator counterpart. This is possible because the dynamotor can have smaller airgaps, lower excitation currents, and smaller field structures.

Dynamotor losses can be grouped into rotating and electrical categories. Rotating losses are made up of bearing, brush, and air friction (windage) losses. Electrical losses are due to copper losses in the armature and field windings and iron losses. With the exception of field losses, which are constant, all dynamotor losses increase as the armature speed increases. This relationship is shown in Fig. 1-69. (3)

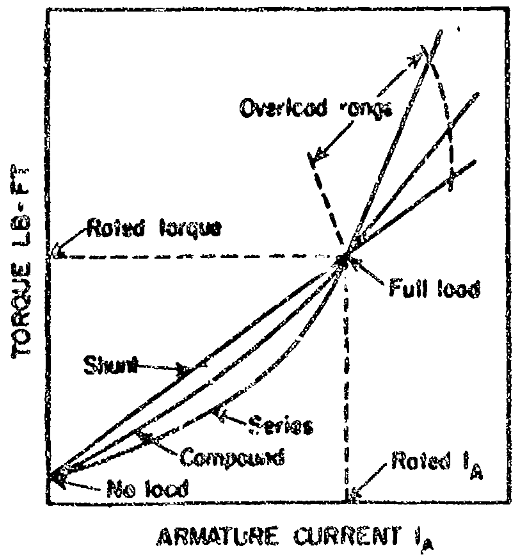


Fig. 1-67. Armature current-torque characteristics of dynamotor primary windings.

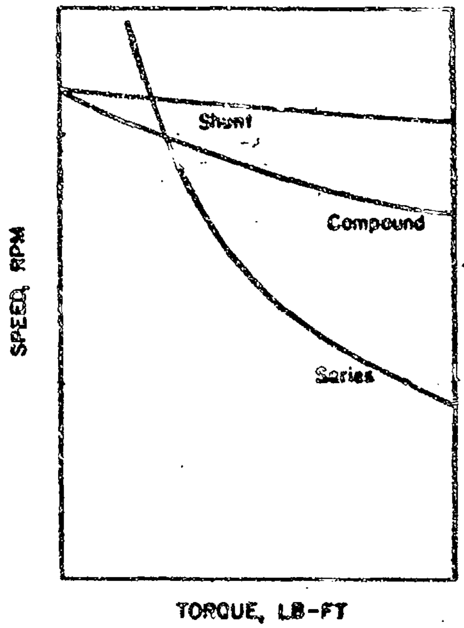


Fig. 1-68. Speed-torque characteristics of dynamotor primary windings.

Dynamotor efficiency is also a function of the rated power output as shown in Fig. 1-70. The curve shows a rapid drop in efficiency below 80 watts output. This characteristic may be attributed to less-than-optimum design parameters commonly used in the smaller units, and to the fact that winding insulation occupies a larger percentage of the copper space.

BRUSHES AND COMMUTATORS

Several factors which influence brush operation and life are lineal speed of the commutator, brush spring pressure, current density in the brush, brush temperature, the coefficient of friction between brush and commutator, and brush and commutator materials.

For dynamotor operation, the first three items are invariant, since they are determined at the time of manufacture. However, it should be noted that the actual current density will be somewhat higher than the densities calculated from the physical cross section of the brush. Because the brush cross section usually does not fully contact the commutator surface due to play in the brush holder and distortion of the holder supporting structure under stress, the brush face frequently has a slightly longer radius of curvature than the mating commutator. This results in a sy-

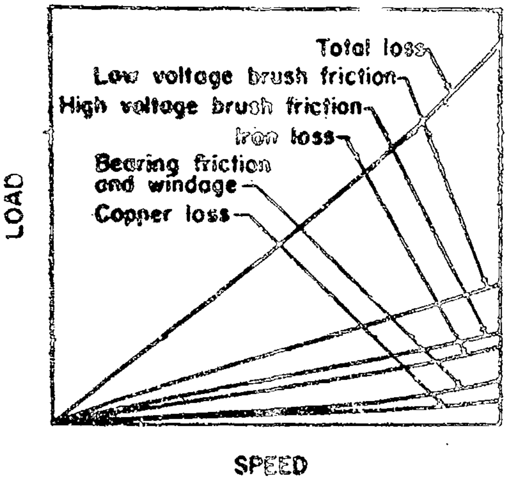


Fig. 1-69. Losses vs. speed relationship for typical dynamotors.

nificantly reduced contact area compared to the nominal brush contact area. Higher current densities cause higher brush operating temperatures. The current flow from the brush surface to the commutator divides into the several paths as shown in Fig. 1-71. (3) These paths are (a) the area of point-contact, (b) adjacent areas in which there are free particles of carbon, graphite, copper or other conducting dust, and (c) the open gap, across which some current will flow in the form of an arc. Arcing over the open gap, if sufficiently intense and prolonged, will damage the commutator surface film, and the effects of this damage will be reflected in increased brush wear and poor overall brush performance, particularly at high altitudes.

Brush performance can also be affected by arc-over on high-voltage brush holders. This is caused by brush dust attracted and held by brush holders made of arc-tracking materials. Such arcing results in complete breakdown of the insulation. Proposed specifications will specify non-arc-tracking brush holder insulating material.

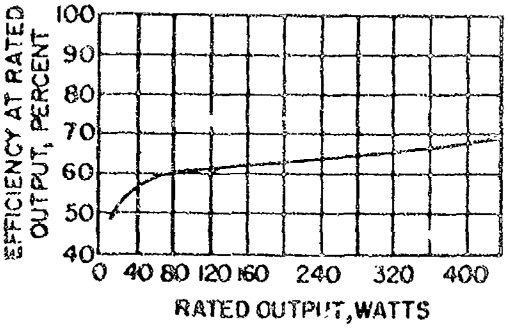


Fig. 1-70. Efficiency vs. rated output for typical dynamotors.

Commutator Surface Film

The commutator surface film, which is developed after a short period of use, is probably the most important single factor affecting brush operation and life. When a clean new brush and commutator combination is put into operation, the highly polished surfaces are in intimate contact. This contact may be so close that the surfaces in the area of contact are subject to seizure or welding, caused by the strong attractive forces of the surface atoms. Since these forces are effective only within a very short range, a boundary film of separation is usually adequate to reduce the effects of these forces by placing the surfaces out of their effective range.

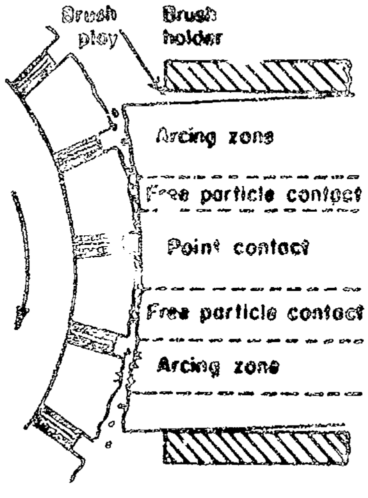


Fig. 1-71. Enlarged view of brush-commutator interface. (National Carbon Co.)

At normal atmospheric pressure, this lubricating boundary film ideally consists of absorbed moisture, oxygen, copper oxide, and carbon. The oxygen and water are derived from the atmosphere, the copper oxide and carbon from slight high-temperature vaporization of the brush and commutator surfaces, mainly as a result of arcing at the brush-commutator interface, and partly from mechanical friction. The formation of a satisfactory surface film on a new commutator may require a run-in period of from several minutes to several days, depending upon brush hardness, interface temperatures, lineal speed of the commutator, brush pressure, and other factors. On some brush-commutator combinations, if the current density is too low, a

commutator film may not form and, in fact, existing films may be destroyed. When this happens, particles of copper thrown off by the commutator may cause commutator threading (grooving of the commutator surface by fine parallel lines) and the brush surface may exhibit copper picking (small particles of copper embedded in the face of the brush).

Brush Wear

It is difficult, if not impossible, to pin down the exact causes of brush wear, since all the factors involved are more or less interrelated. Other than the commutator linear speed and brush pressure, brush wear depends upon the coefficient of friction between the brush and the commutator. In turn, the coefficient of friction depends upon brush temperature (related to current density) and the amount of water vapor and oxygen present (related to altitude).

The rate of wear of a brush (for a particular brush-commutator combination and set of operating conditions) will be affected by the brush pressure. Proper brush pressure is a requisite for best brush performance and life. The range of suitable pressures for a given machine is determined by the type of brush, the load to be handled, and peripheral speed of the commutator. If brush pressure is too low, imperfect commutation will result, causing excessive arcing with resultant damage to the film and undue brush wear. Excessive brush pressures produce unnecessary friction losses and severe wear on both the commutator and brush, and may even cause mechanical instability of the brush. At low pressures, electrical wear predominates whereas at high pressures mechanical wear is greater. Figure 1-72 shows this characteristic for an electrographitic brush although a similar effect may be observed with any brush type, except for a change in the range of optimum pressures. (3) When a new brush is first installed, the brush pressure is initially high due to maximum compression of the spring as well as the fact that the brush is not properly seated until a suitable run-in period has transpired. As the brush wears, the pressure decreases. Brush wear beyond the point of minimum pressure (when the spring has been extended to the permissible limit) will increase rapidly. To keep the pressure from falling too low, it is usually recommended that the brush be replaced when worn to between 2/3 and 3/4 of its original length. Experience shows that the positive and negative brushes do not always wear at the same rate. When

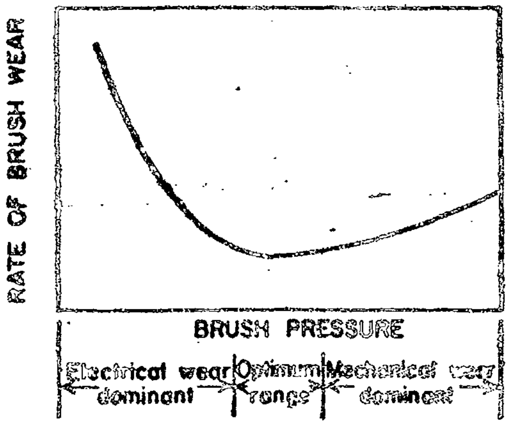


Fig. 1-72. Brush wear rate vs. brush pressure for an electrographitic brush.

the brush exhibiting the greater wear rate has reached the limit of permissible wear, it is advisable to replace both brushes so that they operate, as nearly as possible, under the same pressure. A further reason for replacing brushes in pairs is to avoid using brushes of dissimilar materials on the same commutator. The film formed by some brush materials will act as an abrasive for other brush materials. This situation has been known to reduce brush life by a very high factor.

The other aspect of brush wear, coefficient of friction, is dependent upon the formation and retention of a suitable commutator surface film. For a given brush, the coefficient of friction will be a function of the brush temperature, as shown in Fig. 1-73. (3) It should be noted that temperatures are not uniform over the brush face because the temperatures developed are functions of the

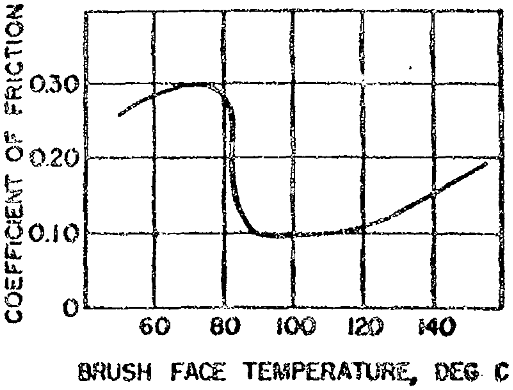


Fig. 1-73. Brush wear rate (coefficient of friction) vs. interface temperature for an electrographitic brush. (National Carbon Co.)

current density and mechanical friction. Variations in current density are due to the difference in the radius of curvature of brush and commutator, as shown in Fig. 1-71. Here the maximum temperature due to electrical heating is found in the arcing zone, with progressively lower temperatures in the free-particle and point-contact zones. Conversely, the temperature distribution due to mechanical friction shows the highest temperature at the point-contact zone, with progressively lower temperatures in the free-particle and arcing zones. Measurement of the resultant temperatures ascribable to both sources at any one point has never been undertaken with any success, except to establish that the brush temperatures are not homogeneous.

Although the exact relationship that exists between the coefficient of friction and the rate of brush wear is rarely explicit, it is reasonable to assume that brush wear will increase as the friction between commutator and brush increases. Figure 1-74 shows this relationship for an electrographitic brush. For this reason, any interference with the commutator surface film will bring about an increase in the coefficient of friction and, therefore, the rate of wear. Since the commutator surface film is composed of copper oxide, carbon, water vapor, and oxygen, any condition which removes any one of these

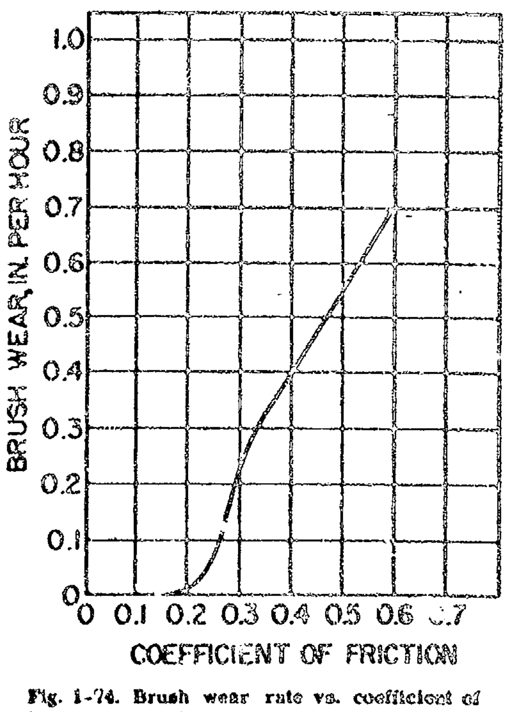


Fig. 1-74. Brush wear rate vs. coefficient of friction for an electrographitic brush.

constituents will change the composition of the film and subsequently the rate of brush wear.

Commutator Poisons

Commutator surface films are subject to deterioration by atmospheric contaminants, which are called "commutator poisons." These poisons act as reducing agents and tend to react upon the metallic constituents of the film; in sufficient quantity they will destroy the film. Almost any organic compound, solvent, or corrosive vapor will operate upon the film, including acid fumes, chlorine and other halides, tobacco smoke, carbon tetrachloride, paint fumes, and turpentine, alcohol, and oil vapors.

The effects of these poisons upon the surface film is immediate, severe, and sustained. A striking example of the effects of carbon tetrachloride was observed when this solvent was used some distance away from a d-c machine. Prior to this occurrence, the measured coefficient of friction of the brush-commutator combination was suitably low, but within 5 minutes after the container of solvent had been opened to the air, the coefficient of friction doubled. Within 10 minutes, the characteristic brown mirror polish of the commutator began to show raw streaks of copper and became grooved and pitted. The polished surfaces of the brushes became roughened and exhibited pronounced copper picking. This condition remained for over 6 hours, although the carbon tetrachloride had been in use for only a few minutes. During these 6 hours, the rate of brush wear doubled. This example is particularly significant because carbon tetrachloride is commonly used as a grease solvent. As a note of interest, many motor manufacturers frown upon the practice of using this solvent upon or near any commutator (or slip-ring) type machine. Tobacco smoke is equally destructive; just a puff or two will double the brush friction for several minutes.

Commutator surface films may be affected adversely also if water vapor or oxygen is removed. This may occur at high altitudes, where the concentration of water and oxygen decreases. Figure 1-75 shows the change in wear rate versus altitude. Experimental evidence shows that the presence of water vapor and oxygen in the film aids commutation by a lubricating action. When a commutator is operated at high altitudes, these lubricants are no longer present in sufficient

quantities. In addition, increased arcing caused by the decreased pressure adversely affects the wear rate.

The addition of some metallic halides to the brush has been found to increase brush life at high altitudes by promoting the formation of a film with slightly different constituents, but one that is equally effective as a lubricant. Barium fluoride (BaF_2) has gained favor for this purpose, and the brush wear rate for a brush so impregnated is shown in Fig. 1-75. The amount to be added is determined by the altitude range. Experiments have indicated that adding between 5.5 and 7.0 percent barium fluoride will enhance high altitude performance; the brush in curve B of Fig. 1-75 had 6 percent added. The data shown in Fig. 1-75 is all the more significant since the effective operating length of most brushes is 1/4 to 3/8 inch.

A proposed specification for airborne applications requires that at 60,000 feet no brush shall fail before 350 hours of operation and that the average operating life prior to brush failure, if any, of all dynamotors tested shall be not less than 500 hours.

ELECTRICAL PROBLEMS

Flashover

If an increase in secondary currents is rapid enough and of sufficient magnitude to distort the magnetic field around the armature, high transient voltages may be produced between adjacent commutator segments which, if high enough, will lead to flashover. The normal potential difference between adjacent segments (for a given output voltage) will increase as the number of segments of the commutator decreases. Therefore, the likelihood of flashover is greater with small-diameter commutators (having fewer segments) commonly found in small high-speed units. Sustained flashover will cause carbonization of nearby insulation, and will eventually result in total failure. For a given load, flashover is more likely to occur at high altitudes.

Corona

Corona is a common occurrence at high altitudes if high voltages are present at points having small radii of curvature. Once initiated, corona will be sustained until the ionizing potential has been reduced substantially below the starting voltage, as shown in Fig. 1-76.

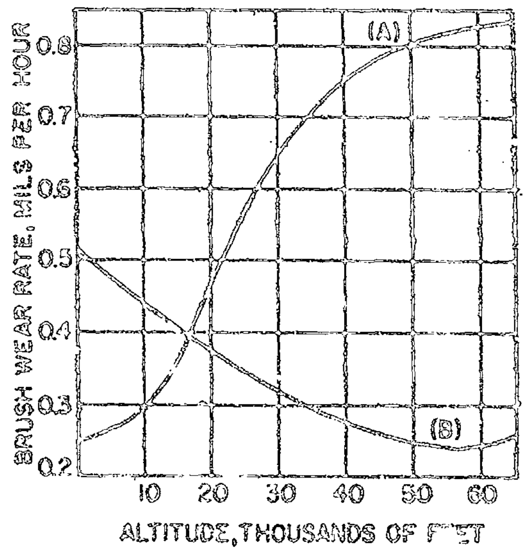


Fig. 1-75. Brush wear rate vs. altitude for (A) Normal brush and (B) Brush treated with barium fluoride. (Note: Commutator speed, brush pressure, current density, held constant.)

The effects of corona are manifested in two ways. One effect is the deterioration of insulation in the vicinity of the discharge due to the production of ozone. Severe corona, if sustained, will cause carbonization of any organic materials present.

A second effect of corona is manifested by the propagation of radiated energy in a broad spectrum ranging from 10,000 cps to over 1.0 Mc at voltages up to [illegible]0 mv.

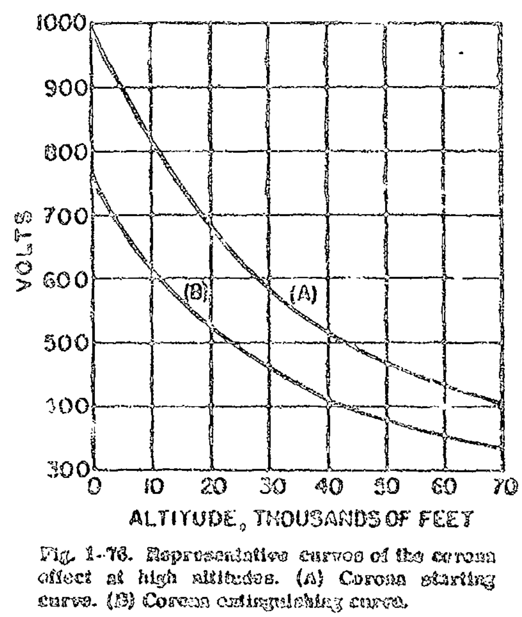


Fig. 1-76. Representative curves of the corona effect at high altitudes. (A) Corona starting curve. (B) Corona extinguishing curve.

Although this aspect of corona has no effect upon the dynamotor itself, the radiated energy may cripple nearby communications equipment.

R-F Noise

R-F noise generation is an aggravating dynamotor problem. Such noise is produced at the brush-commutator interface where commutation produces sparks. A secondary source of noise, brush bounce, is caused by vibration or commutator eccentricity. Brush bounce tends to lift the brush off the commutator surface, the effects becoming more pronounced as the armature speed increases. The spectrum covered may range up to 200 Mc, both conducted and radiated. The noise intensity increases as the output current increases; intensities up to 3500 microvolts have been measured. The conducted noise level is much higher than the radiated level, and tends to peak between 5 and 15 Mc. The conducted noise level may be reduced by suitable filtering. The effects of radiated energy may be minimized by suitable shielding, increasing the distance between dynamotor and the equipment troubled, ensuring excellent metal-to-metal bonding of the frame-to-mounting structure, and connecting small mica capacitors (0.01 to 0.005 mf) across each pair of brushes.

A secondary source of r-f noise may be found within the dynamotor armature. The armature shaft ends are normally insulated from the frame by a film of lubricant. The armature core and shaft may build up a static charge due to the high speeds and the capacitance that may exist between the core and the windings. When this potential becomes high enough, it may arc through the lubricant. This form of radiated energy may be avoided by using a grounding brush connected between frame and shaft.

Noise Filters. Specifications for inductors and capacitors for r-f filtering are included in MIL-D-24A.

MOUNTING

Dynamotors are commonly mounted integrally with the equipment for which they are furnishing power by means of either wrap-around straps with bolt holes or mounting feet cast integrally with the frame. If a dynamotor is to be mounted directly upon an equipment chassis, it is good practice to brace the chassis beneath the machine to prevent chassis distortion due to the high weight per-sq-ft common to these components. Further, because the dynamotor is a relatively heavy component, it is inadvisable to use shock or vibration isolators to isolate the equipment from the vibration produced by the armature rotation; the preferred practice is to isolate the individual components from the chassis proper, and to mount the dynamotor firmly to the chassis.

Most dynamotors use ball bearing armature supports. These bearings are primarily designed to support radial thrusts only, because the dynamotor generally does not have an external mechanical load which might produce other forces. Therefore, the dynamotor should be mounted so as to have the shaft axis as close to horizontal as possible. Where a unit may be subjected to external vibration or acceleration, the shaft axis is best positioned perpendicular to these forces, so that longitudinal armature motion cannot distort the end caps (or bells) which support the brushes and shaft bearings. End cap distortion may result in damage to the commutator surface film or mechanical interference with armature rotation.

LUBRICATION

Dynamotors are frequently supplied with sealed bearings and may not require relubrication during their lifetime. Those units that do require periodic lubrication may use grease prescribed by MIL-G-3278, Grease; Aircraft and Instrument (For low and high temperatures). Under this specification, a grease suitable for low-temperature use must be capable of permitting a 204K Conrad type 8-ball bearing to complete one revolution within 5 seconds at -65 F with not more than 2000 gm-cm of torque applied. The choice of lubricant for low-temperature use can be determined, to some extent, by the type of unit to be lubricated. The temperature at which the armature will commence rotation as the ambient temperature is increased from very low values with a given type and grade of lubricant will be lower with units of larger size. The reason for this behavior is that dynamotors with high output are frequently compound-wound, with series windings capable of producing high starting torques, whereas small units usually have only shunt windings.

High-Temperature Lubrication

The choice of lubricants for use at high temperatures will be determined by the maximum temperature to be encountered. This

choice is not simple, since the same lubricant must be suitable at low temperatures. The problem exists of obtaining a lubricant which will not solidify at -65 F, but will also be capable of surviving at temperatures as high as 250 F or higher, and which will not vaporize nor condense upon the commutator. Recent developments using synthetic organic compounds classified as polyalkylene glycols have shown this group of lubricants to have low pour points with the additional advantage that high temperatures do not cause carbonization or solidification. For this reason, they may prove satisfactory as a vehicle for dry-type lubricants such as molydenumdisulphide or colloidal graphite. Another experimental process, electrofilming of the bearings, consists of spraycoating the metal with a microscopic layer of graphite-metal which is then baked at high temperatures to produce an intimate bond between the coating and the metal base. Electrofilming is advantageous because it avoids the trouble of periodic lubrication and the vaporizing effects of lubricants.

Miniaturized dynamotors tend to operate at higher temperatures, putting additional strain on the chosen lubricant. A simple method for determining the efficacy of a lubricant is to monitor the input current to an unloaded dynamotor operating at the desired temperature. Any significant increase in current is usually indicative of increased friction due to lubricant failure.

TEMPERATURE RISE AND DUTY CYCLES

The temperature rise of a dynamotor is always specified for a particular duty cycle and maximum ambient temperature. Temperature rise is determined by the point at which the rate of heat generation equals the rate of heat dissipation. Since the rate of heat absorption by the surroundings is determined by the temperature difference between the dynamotor and the surrounding atmosphere, temperature rise ratings are always defined at a specified maximum ambient temperature. Furthermore, the temperature rise for a particular unit under a given load will vary with the ambient temperature because the temperature coefficient of the materials used gives rise to resistance changes which affect the I^2R heating.

The rated duty cycles of dynamotors are either continous or intermittent, though some units may have both types of ratings. Continuous duty is continuous full-load operation. Intermittent duty cycles vary from manufacturer to manufacturer; typical intermittent duty cycles might be 10 seconds on, 30 seconds off, 1 minute on, 5 minutes off, or some other comparable cycle at full-load. MIL-D-24A specifies three types of intermittent duty: (1) Duty A, 5 minutes on and 15 minutes off; (2) Duty B, 1 minute on and 9 minutes off; and (3) Duty C, 1 minute on and 29 minutes off. Where a dynamotor has both duty ratings, the intermittent duty rating is higher than the continuous duty rating.

Heat Dissipation. The manner by which heat is dissipated from a dynamotor will vary depending upon operating conditions. Convection cooling is commonly used in sea-level applications, and is usually accomplished by an internal fan mounted on one end of the armature. The efficiency of convection cooling is directly proportional to air pressure and therefore, convection cooling is relatively ineffectual above 10,000 feet.

Radiation cooling is not affected by air pressure, and may be utilized at any altitude. This form of heat dissipation depends on the temperature difference between the source and the heat sink. As this temperature difference decreases, the rate of heat radiation also decreases. The rate of radiation may be enhanced by coating the dynamotor with a dull black finish.

Conduction cooling may be useful at any altitude, and it depends upon the area of contact, temperature difference between source and sink, and capacity of the sink. Good metal-to-metal bonding between the dynamotor frame and the dynamotor supporting structure is essential to good conductive cooling.

SPECIFICATIONS

At the present time there is only one coordinated military specification for dynamotors. This specification, MIL-D-24A, dated 15 August 1955, is primarily a specification delineating military requirements for: r-f interference, dielectric strength, insulation resistance, dynamic balance, load, temperature rise, maximum and minimum ambient temperature, vibration, shock, low-temperature/high-altitude operation, moisture resistance, corrosion and fungus resistance, life, duty cycle, brush life, weight and dimensions, ripple, regulation, efficiency, enclosures, and overvoltage (input).

Table 1-14—Dynamotor Nomenclature Used in Military Specifications

Symbol	Description
DM	Dynamotor installed in a mobile ground electronic gear carrier.
DY	JAN nomenclature dynamotor
V	Dynamotor installed in a ground vehicle other than the DM group (i.e., tanks, etc.)
G	Ground, general use
U	General Utility
R	Radio
C	Communications (Receiving and Transmitting)

The specification incorporates operating parameters for certain specific types of dynamotors. (Refer to Tables 1-14 and 1-15.) Table 1-15 lists the pertinent characteristics of the various types procurable to MIL-D-24A. They are not intended for use above 10,000 feet altitude. It should be noted that these types are only representative, and that any dynamotor which conforms to the overall requirements of the specification will be acceptable.

There are a number of single service specifications which may be used for dynamotor procurement. This group is tabulated in Table 1-16. Dynamotors covered by these specifications were designed primarily to be used with particular equipments.

Table 1-15A—Dynamotors of MIL-D-24A, Electrical Properties

Type designation	V_{in} (vdc)	I_{in} (amp)	V_{out} (vdc, nominal)	I_{out} (amp)	Ripple (% max)	Regulation (% max)	Efficiency (% min)	Duty cycle
DM-34*	14	2.8	220	0.08	2.27	17	45	Cont.
DM-35*	14	10.7	625	0.225	2.4	17	60	Int. A
DM-36*	28	1.4	220	0.08	2.27	17	45	Cont.
DY-102/VRC*	28	9.2	625	0.225	2.4	17	60	Int. A
DM-40†	14	3.6	172	0.138	2.0	15	45	Cont.
DM-41*	28	1.7	172	0.138	2.0	15	45	Cont.
DM-42*	14	46.9	515 1030 8 vac	0.215 0.260 0.220	2.0	12	60	Cont.
DY-93/VRC*	28	23.0	515 1030 8 vac	0.215 0.260 0.020	2.0	12	60	Cont.
DM-43*	28	1.9	250	0.050	2.0	18	42	Cont.
BD-77*	14	40.0	1000	0.350	2.0	12	60	Int.
DY-88/VRC-2X	28	7.0	600	0.175	2.0	15	60	Cont.
DY-97/GRC-9	7 14 28	20.9 10.0 5.0	580	0.100	6.0	15	33 35 35	Cont.
DY-133/U	28	3.0	12.9	3.5	3.0	10	55	Cont.
DY-65/VRC-2		32	600	0.175	2.0	18	60	Cont.
DY-134/GRC-9X	28	3.0	530	0.100	8.0	15	35	Cont.

* Inactive for new design.
† Installed in a mobile ground electronic gear carrier.

Table 1-15B—Dynamotors of MIL-D-24A, Thermal and Mechanical Properties

Type designation	Ambient temp (deg C, max)	Field temp rise (deg C, max)	Speed (rpm, nominal)	Enclosure type	Weight (lb, max)	Nominal dimensions (in.)		
						Length	Width	Height
DM-34*	50	[illegible]	7000	Totally enclosed	4.75	4.9	2.75	3.13
DM-35*	50	45	8000	Open protected	9.3	7.9	3.5	5.38
DM-36*	[illegible]	[illegible]	[illegible]	Totally enclosed	4.75	4.9	2.75	3.13
DY-102/VRC*	50	45	7200	Open protected	9.75	7.9	3.5	5.38
DM-40†	55	NA	5000	Open protected	7.2	6.9	4.75	3.5
DM-41*	55	NA	5000	Open protected	7.2	6.9	4.75	3.5
DM-42*	55	NA	7500	Open frame	32	10.5	5.9	5.7
DY-93/VRC*	55	NA	7500	Open frame	33	10.6	5.9	5.7
DM-45*	50	60	7000	Totally enclosed	3.0	4.7	3.75	3.0
BD-77*	55	NA	5800	Totally enclosed	41.8	11.25	7.25	6.9
DY-88/VRC-[illegible]	55	NA	5200	Open protected (Fan cooled)	10	7.4	4.75	4.4
DY-97/GRC-9	55	NA	5400	Open protected (Fan cooled)	14.5	10.2	4.13	5.0
DY-133/U	55	60	6000	Open protected (Screen opening)	9.5	7.3	3.9	4.4
DY-35/VRC-2	55	NA	5200	Open protected (Fan cooled)	10	7.4	4.75	4.4
DY-134/GRC-9X	55	NA	[illegible]	Open protected (Fan cooled)	9.4	[illegible]	3.83	4.7

*Inactive for new design.
†Installed in mobile ground electronic gear carrier.

TYPES AVAILABLE

This section is devoted to discussions of the types of dynamotors and variations within types.

Fields

Dynamotor fields are of three different types: permanent magnet, shunt-wound, and compound-wound. For units with power outputs below 75 watts, many manufacturers are using permanent magnet (pm) fields, in an attempt to increase the very low efficiency (15 to 25 percent) common to these small units. This has the virtue of increasing efficiency up to 40 percent, but there are some very distinct disadvantages. The magnets may be permanently demagnetized or their fields

Table 1-16—Dynamotor Military Specifications

Specification MIL-D-	Date	Amendment	Types covered
24A	15 Aug. 1955	1 - 16 April 1956	*
5886(USAF)	21 July 1950	—	DY-63/ARC
6676B(USAF)	17 Jan. 1952	1 - 15 Oct. 1952	DY-22/ARC-3
7303(USAF)	3 Dec. 1951	1 - 28 Oct. 1952	DY-21/ARC-3
7450(USAF)	6 Mar. 1953	1 - 4 June 1954	DY-84/ARN-14A
8014(USAF)	7 Jan. 1953	—	DY-87/ARN-60A
8309(USAF)	13 Apr. 1953	—	PE-180
8364(USAF)	5 Aug. 1953	—	PE-186
9040(USAF)	22 Apr. 1953	—	DY-104U
9227A(USAF)	19 Mar. 1954	—	DY-76A/AIC-10
9321(USAF)	19 Jan. 1954	—	DY-92U
9283(USAF)	10 Nov. 1953	—	DY-77/AIC-13
13258(SigC)	11 Feb. 1954	—	DY-44U

* DM-34, 35, 33, 40, 41, 42, 45; BD-77; DY-65/VRC, 85/VRC, 96/VRC, 197/GRC, 102/VRC, 133/U, 136/GRC.

may be distorted by high transient loads. These loads may induce high secondary currents whose resultant magnetic field can permanently distort the molecular alinement of the field magnet. The magnets may be permanently damaged by exposure to high temperatures or the magnetic field may be distorted or weakened if placed too near a steel chassis or bulkhead.

Units with power outputs up to 200 watts commonly use a shunt-wound field, while machines with ratings above 200 watts frequently have compound field windings. Compound field windings are preferred where (1) the duty cycle is intermittent, (2) low-temperature operation is expected, and (3) to reduce starting currents. Applications involving intermittent duty cycles usually require that the armature come up to speed with minimum delay; typical requirements for military equipment state that the dynamotor must develop at least 75 per cent of rated output within 250 milliseconds. The high starting torque of compound-wound units permits this and, in addition, also provides more torque for low-temperature starting in order to overcome the drag of lubricants which are viscous at low temperatures. The lower starting currents frequently found in compound-wound units are favorable for increased life of input brushes and starting relays. Unlike compound-wound motors, the series winding is not cut out by a centrifugal switch when the unit has come up to speed.

Armature Windings and Commutators. Dynamotors are available with single or multiple inputs or outputs, or both. For practical limitations, the maximum number of commutators is four, and a typical unit may provide three inputs and one output, two inputs and two outputs, or one input and three outputs. Multiple input windings (one to a commutator) are usually rated for different input voltages, so that a unit with input windings for 6 and 12 volts may operate from either 6 volts, 12 volts, or, if suitably connected, from 18 volts. Multiple output windings may be treated in the same manner. It is important, however, to observe the proper polarities so that windings are not inadvertently connected in opposition, and that the voltage rating of the insulation is not exceeded. Since the generated voltage prior to rectification by commutation is a-c, a number of dynamotor manufacturers have substituted slip rings in place of the commutator, and thereby provide an auxiliary a-c output.

Power Ratings

Most manufacturers produce a line of dynamotors with outputs ranging from 10 watts intermittent up to 500 watts continuous. Within a given frame size, it is usually possible to obtain almost any combination of input and output voltages, provided the total power involved does not exceed the capacity of the frame size. Where a unit has a multiple power output, the total is determined by adding the individual outputs. Generally speaking, a comparison of two units having the same total power output will show that the unit with multiple outputs tends to have a slightly higher overall efficiency due to distributed currents in the multiple windings.

Voltage Ratings

Commercially available units are commonly designed to operate from d-c sources supplying voltages in the range from 6 to 230

volts. Since most dynamotor applications are mobile, the majority of commercial units are wound for 6, 12, or 24 volts, while dynamotors procured to MIL-D-? have designed to operate from 7-, 14-, or 28-volt sources. For best operation, the input voltage should be held to within 10 percent of the rated voltage, since voltage excursions beyond this range will reduce the already low efficiency and will shorten life due to increased temperatures.

Output voltages obtainable range from 6 volts through 1000 volts. Although most units provide output voltages greater than the input voltages (step-up operation), dynamotors are available that will also perform step-down functions and combined functions. A typical unit in this group might operate from a 12-volt source to provide 6.3 volts for tube heaters and 300 volts (or more) for plate and screen.

Regulation

Voltage regulation on most dynamotors is rather poor, with typical regulation characteristics averaging 5 to 20 percent. These figures would be completely unacceptable for any other type of power supply and, except for the fact that most mobile communications equipments are not especially sensitive to voltage fluctuations of this magnitude, dynamotors would find little application. Comparison of different units seems to indicate that regulation improves with units having higher rated armature speeds.

Ripple

The total ripple content in the dynamotor output will average about 1 to 1-1/2 percent, depending upon load. That portion of the total ripple due to commutator modulation will increase as the currents through the commutator increase. Filters may be inserted in input and output circuits to reduce the magnitude of ripple and harmonics.

Efficiency

Reference to Fig. 1-70 shows that dynamotor efficiency is a function of the rated output. The efficiency of units with higher ratings than those shown in Fig. 1-70, reaches a maximum of 70 to 75 percent, while most units with 100- to 200-watt output average 60 percent. For any given unit, efficiency drops rapidly as the load is reduced below 60 percent of the rated figure. Figure 1-77 shows the efficiency characteristics of a typical dynamotor. The primary factors con-

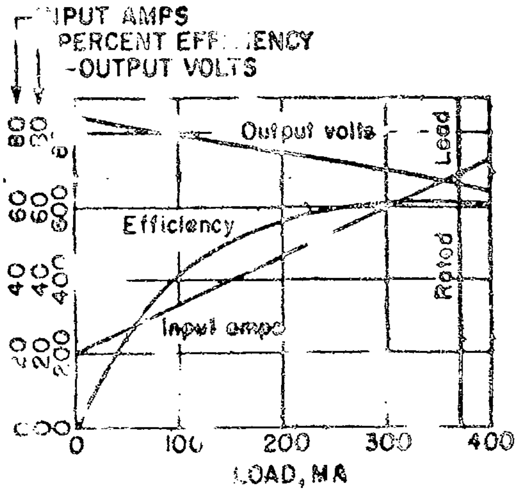


Fig. 1-77. Typical operating characteristics of a dynamotor.

trolling efficiency are size and armature speed. High operating speeds usually result in lower overall efficiency due to increased mechanical losses, as shown in Fig. 1-69. The efficiency figures supplied by most dynamotor manufacturers were derived under optimum conditions, and the user will find operating efficiency to be somewhat less than the published figures.

Weight, Shape, and Dimensions

The correlation between the weight and volume of a dynamotor and its rated capacity is quite close, with typical units requiring approximately 1.6 cu in. per watt output, continuous duty, at a weight of about 0.08 pound per watt. Most dynamotors are cylindrical, although many units are almost rectangular. Casing lengths range from 5 inches up to 13 inches, while widths and heights (exclusive of externally mounted items) range from 3 to 7 inches.

Enclosures

Dynamotors are available with four different types of enclosures: explosion-proof, dust-proof, totally enclosed, and open protected. The explosion-proof case is designed to prevent sparks at the commutators from igniting the explosive atmosphere. If a dynamotor is operated in an excessively dusty atmosphere, dustproof enclosures are useful to protect the commutator and bearings from excessive wear. The totally enclosed dynamotor is designed for use where atmospheric conditions are corrosive or otherwise harmful.

Open protected enclosures may be used where the operating environment presents no unusual hazards.

Brushes

Input brushes for step-up operation generally must handle more current than the output brushes, while the reverse is true for step-down operation. To equalize the wear rates of the input and output brushes, larger brushes and different materials are used to equalize the current densities. Tests have confirmed that input brush life is greater with continuous operation than with intermittent duty because the high starting currents are not applied as frequently. "Low-drop" brushes will effect minimal losses at high current densities and they should be used only on input commutators. Conversely, "high-drop" (high voltage, low current) brushes are best used with output commutators. The reverse holds true in step-down operation. The color coding for input and output leads is shown in Table 1-17.

Accessories

Dynamotor accessories include filters, starting relays, blowers, vibration and shock isolators, and connectors. Many dynamotors are constructed with armature shaft extensions protruding from one or both ends of the machine. These extensions may be used for low-power mechanical takeoff to drive gear reducers, contact breaker points, blowers, and the like. This feature is particularly desirable in applications where space, weight or power are at a premium, since the necessity for a separate blower motor is eliminated.

ENVIRONMENTAL CONSIDERATIONS

Temperature

The maximum ambient temperature specified by MIL-D-24A ranges from 45 C to 85 C, with most units operable up to 55 C at rated load. Conformance to the maximum specified ambient temperature is necessary to prevent the total internal temperature (ambient plus rise) from exceeding the limit set by the winding insulation and temperature-sensitive components. Possible effects of operation beyond the specified total internal temperature include shorted armature turns, armature windings separating from their commutator segments, destruction of bearing lubricants, excessive brush wear, and reduced efficiency due to increased I^2R losses.

Successful starting and operation in the temperature range of -65 C, the lowest specified in MIL-D-24A, is dependent upon starting torque, lubricant viscosity, and bearing design. If the bearings seize, the possibility of burning out the primary windings is high, and thermal protection should be provided.

Altitude

The effect of high altitudes upon brushes has been previously discussed. If potting procedures used on either the armature or field windings have left voids, it is entirely possible that very low ambient pressures may rupture the material covering these voids, thus leaving the bare copper exposed.

Humidity

High humidity may lower the dielectric strength or the insulation resistance suffi-

Table 1-17.—Color Coding of Dynamotor Leads, MIL-D-24A

Leads	Polarity	Color code*
Single input (or lowest voltage)	Positive Negative	White Black
Dual input (next higher voltage, if any)	Positive Negative	Green Brown
Single output (or lowest voltage)	Positive Negative	Red Blue
Dual output (second highest voltage)	Positive Negative	Red, green tracer Blue, green tracer
Triple output (highest voltage)	Positive Negative	Red, black tracer Blue, black tracer

* White background wire may be substituted using a broad helical stripe for the base color and a narrow helical stripe for the tracer.

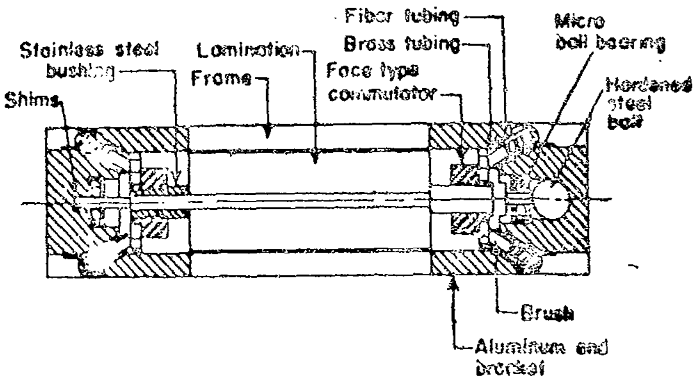


Fig. 1-78. Cutaway of miniaturized dynamotor with face-type commutator.

ciently to cause breakdown and consequent failure. If a unit has high output voltages, excessive moisture in the air may induce flashover or arcing at the output commutator, even in totally enclosed units.

Corrosive Atmospheres

The effect of corrosive atmospheres on brushes has already been treated. For other parts of a dynamotor, standard protective coatings are recommended.

Sand and Dust

The effects of sand upon any high speed precision machine are well known. There is, however, one important point that the reader should note: dynamotors with high voltage outputs may exhibit a tendency, under some conditions, to collect dust at the high voltage terminals. A substantial accumulation may result in arcing about these points.

Shock and Acceleration

There are no shock and acceleration phenomena peculiar to dynamotors other than those previously mentioned under "Mounting."

Fungi

The development of a spore culture under warm moist conditions on or within a dynamotor enclosure may result in eventual malfunction due to interference with the moving parts. Other than shielding or eliminating fungi nutrients, there is no known method of inhibiting these growths.

PRACTICAL SUGGESTIONS

1. For intermittent or low-temperature operation, a compound-wound field is preferred. Thermal protection should be provided.

2. For a given power output, minimum ripple and maximum efficiency may be obtained with low-speed units (if size and weight are not critical).

3. Avoid high transient loads, especially on small units, particularly if they have permanent magnet fields. This will reduce the possibility of flashover or demagnetization.

4. Do not permit brushes to wear beyond the minimum specified length, and replace brush pairs when either brush has worn to the permissible limit.

5. Avoid commutator poisoning as a result of exposure to carbon tetrachloride, tobacco and other smoke, and the fumes of acids, lubricants, paints, and other hydrocarbons.

6. Avoid axial thrusts.

7. Do not overlubricate, and avoid using a lubricant that may vaporize at high temperatures. (See No. 5 above.)

8. Protective coatings should always be used; dull black paint is useful in increasing the radiation emissivity.

9. Avoid using items such as wax-coated capacitors within the dynamotor enclosure. The wax may melt at high temperatures and interfere with the proper operation of the bearings and commutators.

TRENDS AND DEVELOPMENTS

Developments in the field of miniaturization have been extended to d-c power supplies. Dynamotors have been, and are being, developed for particular applications (such as

guided missiles) whose requirements may be summed up as follows:

Input:	6 or 12 volts dc
Output:	150 to 250 volts dc at 15 to 30 ma (2.5 to 7 watts output)
Size:	length of 4 inches, diameter up to 1-1/2 inches
Li. :	5 hours average
Shock and vibration:	operable during accelerations of 10,000 g while the case is spinning at 10,000 rpm.

Figure 1-78 shows a prototype miniaturized unit. Generally, in miniaturized dynamotors, face-type commutators and brushes are used to reduce the case diameter and to minimize the effects of longitudinal acceleration. (2) Printed-circuit face commutators, such as those shown in Fig. 1-78 (in place of the usual copper insert bars) have been used with limited success. For one-shot use, they appear to be adequate and do effect substantial space and weight savings. Another distinct advantage of the printed commutator is that there is less tendency to throw off a commutator segment at very high armature speeds. For example, if the armature speed of, say, 9000 rpm is added to case rotation of 10,000 rpm (in the same direction), the effective total speed of the armature is 19,000 rpm. At this speed, solid commutator bars are likely to be thrown off.

The operating curves of Fig. 1-79 illustrate the characteristic low efficiency of small dynamotors. Alnico V permanent magnet fields are widely used in this type of dynamotor to increase the efficiency.

REFERENCES

1. Siskind, Charles S., "Direct-current Machinery" McGraw-Hill Book Co., Inc., New York, 1952.
2. "Miniaturized Dynamotor, First Quarterly Progress Report," March 15 to August 15, 1953. Signal Corps Contract #DA-36-039-Sc-42711, by Electro Engineering Products Company., Chicago, Ill.
3. "Carbon Graphite and Metal Graphite Brushes," National Carbon Co., New York.

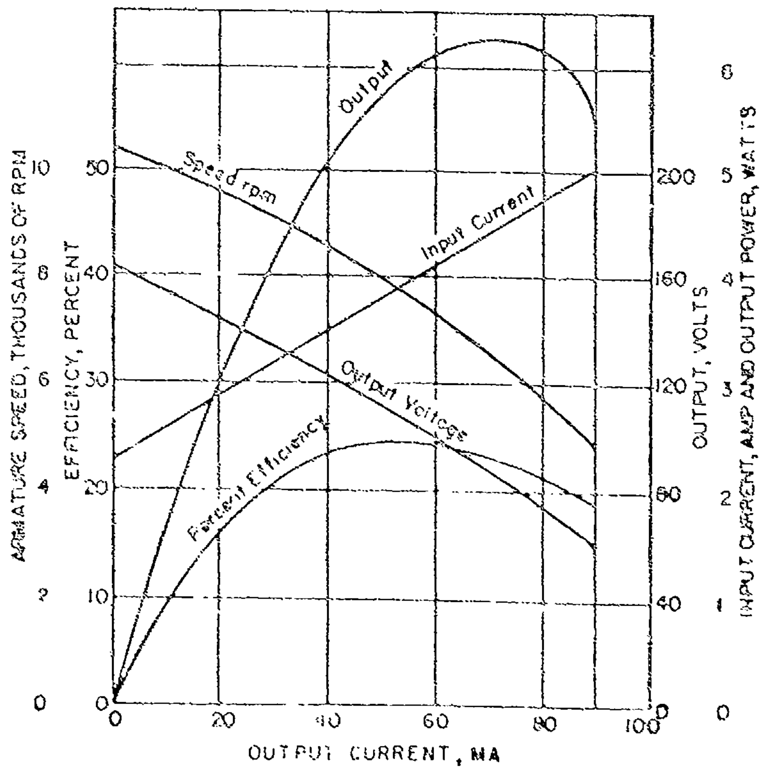


Fig. 1-79 The operating curves of a miniaturized dynamotor similar to the one shown in Fig. 1-78.

TRANSISTORIZED POWER SUPPLIES

Although transistors are being applied to the output of a conventional tube or dry-disk rectifier as a means of regulation, in this book transistorized power supplies are taken to mean the use of transistors as a switch, much as a vibrator operates, to convert direct current to alternating current, which is then rectified to furnish direct current at a new voltage level, regulated or unregulated.

It is reasonably certain that the transistor will eventually supplant the vibrator in this function and that power supplies using transistors as primary components will replace the dynamotor as a power source.

Transistorized power supplies, compared to vibrator or dynamotor supplies, have the advantages of no moving parts, light weight, small size, greater efficiency, longer life, relative immunity to shock and vibration, and small maintenance. Compared to tube power supplies, they have the additional advantage of requiring no warmup period. At present the transistor is limited in the power it can handle, and it is adversely affected by high temperature.

Considerable research is under way to extend the working-temperature range and power-handling abilities of transistors and to develop improved transformers for use in transistorized power-supply systems. While it is too early to be very definitive about the characteristics of such supply systems, the following comments apply to the situation as of December 1957.

OPERATING CHARACTERISTICS

Efficiency. Efficiencies of 60 to 80 percent are fairly easy to obtain. In practice, 90-percent efficiency can be secured if voltage regulation is not needed. The prime controlling factor is the design of the transformer. Operating frequency is also a vital parameter.

Regulation. Conventional regulation techniques may be used with one significant variation: the standard functions of voltage and current regulators should be performed by transistors if high overall efficiency and optimal miniaturization is to be achieved. Transistorized power supplies are commercially available that provide stable output voltage under conditions of varying load current and input source voltage.

Operating Frequency. While the larger proportion of transistorized power supplies currently being manufactured utilize operating frequencies between 400 and 1200 cps, the range of frequencies actually being used or tested extends from 20 to 20,000 cps. The operating frequency is determined primarily by transformer design and filter requirements. Where size and weight are of vital significance, it is desirable to operate at as high a frequency as possible. From the opposite perspective, however, no difficulty is experienced in operating units at frequencies as low as 60 cps, although the transformer and filter become awkwardly large.

A large part of present-day investigation of operational frequency limits is concerned with the transformer of saturable reactor cores, specifically in terms of size, material, and configuration. A cup-shaped core is being tested for efficiency above 15 kc; experiments are being carried out using cores wound with special alloy tapes of varying gauges and widths.

The growing feasibility of operation at higher frequencies is expected to make possible further reductions in size and weight of transistorized power supplies.

Power-Handling Capabilities. The power-handling capabilities of the transistorized power supply at present are limited. Therefore, most currently manufactured power supplies utilizing power transistors fall into power ranges below approximately 80 watts. A few devices exist in which outputs ranging up to 1000 watts, and slightly higher, are provided. Extending the power-handling capabilities of the unit is essentially the problem of increasing the current-carrying capacity of the transistor element itself by increasing the allowable power dissipation of the junction or by reducing losses in the transistor. The power-handling capabilities of some representative commercial supplies are listed in Table 1-18 together with data relevant to input and output voltages and approximate sizes and weights.

Supply-Voltage Requirements. For use in dc-to-dc converters, power transistors are designed and manufactured to function from input voltages of 1.5, 3.0, 6.0, 12.0, 24, or 32 volts dc. This range covers the 24-volt primary sources carried in military vehicles, even including voltages encountered during peak charging intervals. The transistors must

Table 1-18—Operating Characteristics, Weights, and Dimensions of Representative Commercial Transistorized Power Supplies

Input voltage (vdc)	Output voltage (vdc)	Output current (ma)	Output power (watts)	Size (in., approx)	Weight (lb, approx)
6	1000	1	1	2 x 2 x 3-1/2	3/4
12	125	40	5	2-1/2 x 2-1/2 x 6	1-1/2
12	1000	5	5	2-1/2 x 2-1/2 x 6	1-1/2
28	500	50	25	2-1/2 x 2-1/2 x 6	1-1/2
28	240	130	30	2-1/2 x 2-1/2 x 6	2
28	200	250	50	2-1/2 x 2-1/2 x 6	2
28	120	625	75	3 x 3 x 6	2
28	150	500	75	3 x 3 x 6	2
28	250	300	75	3 x 3 x 6	2
28	500	150	75	3 x 3 x 6	2
28	1200	62.5	75	3 x 3 x 6	2
28	250	400	100	3 x 3 x 6	3
28	500	200	100	3 x 3 x 6	2
28	1200	84	100	3 x 3 x 6	2
28	2100	60	125	3-1/2 x 3-1/2 x 6	4
28	500	300	150	3 x 3 x 6	2
28	500	400	200	3 x 3 x 6	3
28	300	600	300	3 x 3 x 6	2
28	500	1000	500	5 x 6 x 8	6

be capable of withstanding twice the nominally rated d-c input voltage.

PHYSICAL CHARACTERISTICS

Size. The physical size of a transistorized power supply is appreciably smaller than that of a vibrator power supply. Operating at higher frequencies promises even greater reductions in size. At higher frequencies, smaller and fewer filtering components will be required. It is also anticipated that transformer core mass can be substantially reduced at higher operating frequencies. At present, production efforts toward reducing size have achieved a volume-to-power output ratio as low as 1/3 cubic inch per watt. Representative dimensions for supplies providing various power output levels are given in Table 1-18.

Weight. The volume and density of the transistor is extremely low; the weight of all associated components is similarly low (transformer core and windings plus filter components) and can be expected to decrease further with higher operating frequencies. Commercial production has already achieved a weight-to-power ratio of 1/10 ounce per watt in certain units.

ENVIRONMENTAL QUALIFICATIONS

Environmental test data is extremely scarce due to the newness of this device and the liquid state of current design. Transistorized power supplies have been hermetically sealed and fully potted for measurement of all performance figures in this section. It can be seen that encapsulating in the potting compound contributes greatly to the ruggedness of the overall power supply, enabling it to withstand prolonged exposure to adverse and severe environments by eliminating relative motion between component parts and sealing out humid and corrosive atmospheres.

A realistic view of the environmental capabilities possessed by some of the better manufactured units may be had by noting the performance figures exhibited when tested to Military Specification MIL-E-5272A(1).

Shock. Transistorized power supplies designed for military applications are required to withstand a shock test calling for 18 impact shock of 15 g, each shock impulse having a time duration of 11 milliseconds. The maximum shock is to be reached in approximately 5-1/2 milliseconds, and the shocks are to be applied in the following directions:

1. Vertically, three shocks in each direction.

2. Parallel to the major horizontal axis, three shocks in each direction.

3. Parallel to the minor horizontal axis, three shocks in each direction.

Units are now in manufacture that continue to function normally during and after such a test.

Vibration. Units are required to undergo vibration of 10 to 55 cps at an amplitude of 0.03 inch (0.06 inch total excursion) in any plane. Manufactured transistorized power supplies meet this test and operate normally during and after it.

Acceleration. Units are mounted on a centrifuge and brought up to rotational speed until a specified radial acceleration is attained. Speed, and hence acceleration, are then stabilized for a period of not less than 1 minute. Units currently available exhibit no mechanical failure or malfunction when tested in this manner at 50 g acceleration for intervals up to 2 seconds.

Temperature. Equipment is required to function under a range of temperatures extending from -54 to 71 C. Commercial units are now available that exceed this range at both extremes.

Altitude. Equipment is required to function at pressures ranging from 30 down to 1.32 inches of mercury, approximating an altitude differential from sea level to 70,000 feet. The pressure may remain constant or may change at a rate as high as 0.5 inch of mercury per second. Again, commercial units are now equal to the test with a wide margin of reserve.

Humidity. Equipment is required to operate in atmospheres of 100 percent relative humidity, exhibiting no effect on the stability of operation. Commercially marketed units are available that meet this requirement.

THEORY OF OPERATION

The following description of one transistorized power supply is typical. (1)

This transistorized power supply consists essentially of a saturable reactor with the requisite number of windings and the power transistors. Operation depends on a switching action accomplished by the power transistors when triggered by signals from a feedback winding of the reactor.

The transistors function in a manner similar to the contacts of a vibrator in that when one is open the other is closed. In practice, these transistors differ from true switches or switch contacts in the following respects: (1) they have intermediate conductance levels between full "on" and full "off," which accounts for some rather high dissipation levels during switching, and (2) they require a reverse power to hold them off at high temperatures.

The transistors operate in a push-pull oscillatory circuit with the transformer or reactor windings arranged to provide positive feedback from the collector of each transistor to its emitter. The operation of the circuit shown in Fig. 1-80 can be described as follows. Assume that transistor A starts to conduct and develops a voltage across the primary winding. The polarity is arranged so that the voltage induced in the feedback winding will drive the emitter more positive. This increases the emitter drive, which further increases the collector current. If the circuit components are appropriately selected, the collector will rapidly bottom; and a voltage approximately equal to the supply voltage will appear across the associated half of the transformer primary winding. Since the windings are out of phase, the opposite collector is driven negative to twice the supply voltage.

In this condition, transistor A must supply sufficient collector current to equal the reflected load current, reflected emitter current, and the transformer exciting current. As long as the core is unsaturated, the exciting current requirements will be very low and, provided the transistor can supply the reflected load and emitter currents, the collectors will remain bottomed. With this voltage across the primary winding, the magnetic flux (ϕ) increases according to the relation $E = N d\phi/dt$. Eventually, the core will become saturated causing the exciting current

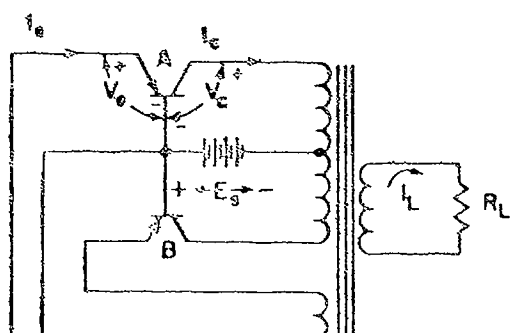


Fig. 1-80. Basic oscillator circuit. Symbols are: A and B, transistors; V_e, emitter voltage; V_c, collector voltage; I_e, emitter current; I_c, collector current; E_g, supply voltage; I_L, load current; R_L, load resistance.

requirement to rise sharply. At some point the transistor becomes incapable of supplying this extra current and the voltage across the primary starts to decrease. This decrease results in decreased emitter drive, which further reduces the collector current. Thus, transistor A shuts off, turning transistor B on at the same time. The next half cycle is identical, except that transistor B conducts. During this half cycle, the core flux is driven to saturation of the opposite polarity.

A grounded base circuit is shown in Fig. 1-80, but design approaches are not restricted to this circuit configuration. Grounded emitter and grounded collector arrangements are equally usable and appear as illustrated in Fig. 1-81.

The significant interval in the overall cycle of operation is that in which the actual switching occurs. During this interval the transistor enters and leaves a region of high dissipation. It is important to maintain low-transistor dissipation, which means that the collector of the conducting transistor must remain bottomed as nearly as possible for the full half cycle.

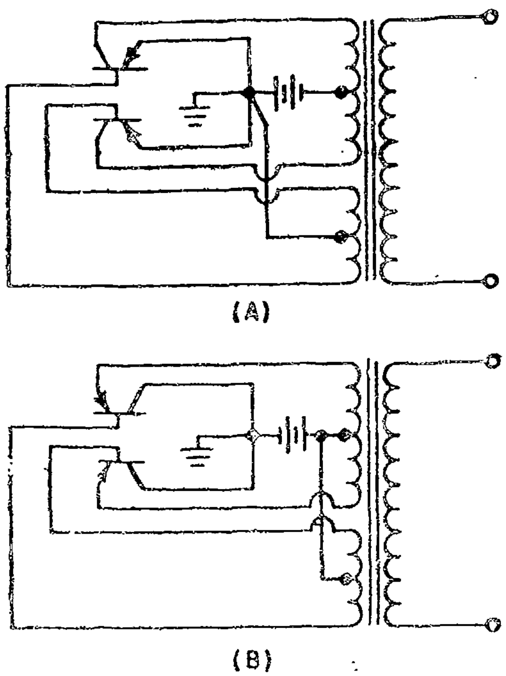


Fig. 1-81. Oscillator circuit configurations. (A) Grounded emitter circuit. (B) Grounded collector circuit.

Voltage Regulation

A number of considerations apply to any voltage or current regulator regardless of the method by which the regulation is obtained. As a matter of background, the major requirements of an ideal regulator as set down by Smyth are listed below. (1)

1. Within the limits of its operating range, the regulator should maintain the output voltage constant independent of variations of supply voltage or load current.

2. The regulator should consume a negligible amount of power from the converter.

3. The regulator should permit the converter to work at its optimum efficiency under all conditions. In particular, it should not increase the transistor dissipation.

4. As a corollary of 2 and 3 above, the regulator should adjust the drain on the supply battery to a minimum at all times.

5. Maximum power obtainable from the converter should not be limited by the regulator.

6. The frequency response of the regulator should be sufficient to handle the highest anticipated rate of change of supply voltage or load current. If this is not possible, the regulator should in no way affect the use of passive filters for this purpose. This requirement also applies to filters used for the purpose of decreasing output ripple.

7. The regulator should be small, lightweight, and as rugged as the other converter components.

8. The regulator should be stable against drifts due to temperature and other causes.

Transistor-Voltage Regulation

While any present conventional form of regulation may be applied to a transistorized power supply, such as a VR tube or other reference source plus the necessary circuitry, it is more elegant (and more efficient) to employ transistors as the regulating component.

To include regulation in simple circuits, feedback from the output to the control winding of the transformer or saturable reactor must be provided. A variety of methods exists by which this may be accomplished. A two-stage transistor amplifier is shown in Fig. 1-82. The first stage is operated with a

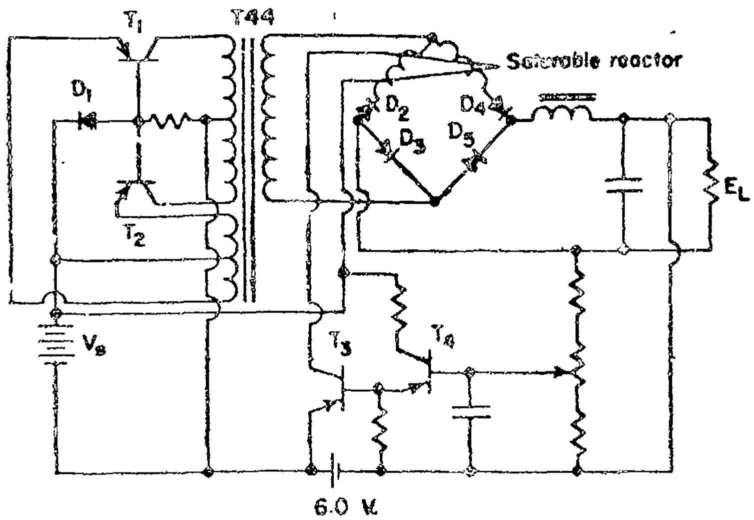


Fig. 1-82. Regulated transistorized power supply with saturable reactor in output circuit and showing transistor control amplifier.

grounded collector to provide the correct impedance match into a high-resistance bleeder across the output. The second stage is a grounded emitter connection with the saturable reactor control winding acting as a collector load. A capacitor between the first stage base and ground is required to prevent instabilities from occurring around the regulator feedback loop.

The change in output voltage over a considerable variation in load current is shown in Fig. 1-83. The regulation is excellent from 10 to 105 ma. Over this range the output voltage changes about 1 volt, or slightly more than 0.5 percent. A supply voltage regulation curve for a current of 105 ma is shown in Fig. 1-84. For a 50-percent increase in supply voltage (from 12 to 18 volts), the output voltage increases only 5 volts or slightly less than 3 percent. While this is not as good as the load regulation, it is ample for many purposes. If improved regulation is desired, it may be obtained through the use of greater amplification in the regulator loop.

Self-Starting Circuitry

In order for the basic oscillator to start, an initial condition of circuit imbalance must exist. When using matched transistors, this imbalance may be inadequate to permit self-starting, particularly under load. This problem can be overcome by use of the circuit of Fig. 1-85. The resistor from the common base lead to the negative supply voltage produces sufficient base bias current to cause oscillation. Once the circuit is oscillating, the diode clamps the bases at ground. The resistor value required depends both on the load current and the transistor gain.

Another method to insure self-starting consists of placing small saturable reactors in series with the load windings. Until the oscillator starts, these reactors have a high impedance. Once the circuit is supplying power to the load, however, the reactors saturate and exhibit low impedance. This technique was developed at the Signal Corps Engineering Laboratories.-(1)

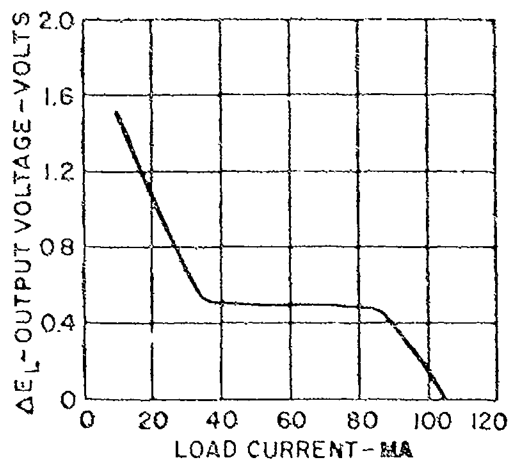


Fig. 1-83. Load regulation for circuit of Fig. 1-82.

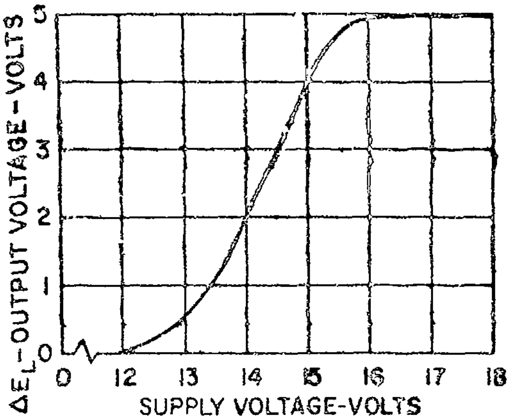


Fig. 1-84. Supply voltage regulation for circuit of Fig. 1-83.

CONTEMPORARY DESIGNS

A multiple output high-power transistorized power supply has been developed for ground systems applications to provide highly stable high-power d-c supplies (16 outputs in all) where size and weight are important factors.

The design incorporates an overload and short-circuit feature so that each supply will sustain partial or dead shorts for any period of time. This equipment was designed to meet MIL-P-11268C (Parts, Materials, and Processes Used in Signal Corps Equipment, dated 18 December 1956) and all parts, materials, and processes conform to this specification where practicable. Easy access for servicing and component replacement is a main feature.

The central power supply consists of three subunits:

1. (a) +300 volts dc at 250 ma
   (b) -150 volts dc at 600 ma
   (c) +150 volts dc at 2.0 amp

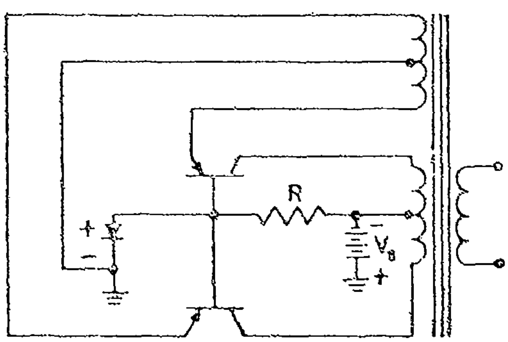


Fig. 1-85. Transistor oscillator self-starting circuit.

2. (a) +28 volts dc at 2.5 amp
   (b) +1.5 volts dc at 1.75 amp
   (c) -6.0 volts dc at 1.5 amp
   (d) -7.5 volts dc at 1.0 amp
   (e) -28 volts dc at 5.0 amp

3. Remote and Metering Unit (Central and Standby)

The standby power supply consists of two subunits:

1. (a) +300 volts dc at 100 ma
   (b) -150 volts dc at 250 ma
   (c) +150 volts dc at 600 ma

2. (a) +28 volts dc at 1.0 amp
   (b) +1.5 volts dc at 0.5 amp
   (c) -6.0 volts dc at 0.4 amp
   (d) -7.5 volts dc at 0.5 amp
   (e) -28 volts dc at 3.0 amp

The 16 outputs of this multifunctional unit are evaluated in terms of regulation, stability, ripple, and output impedance in Table 1-19.

Experimental Unit. The circuit of a transistorized power supply currently undergoing final tests, but not in final production as of September 1957, is shown in Fig. 1-86. This circuit features voltage regulation that tends to hold the output voltage constant in spite of varying source voltage or varying load current.

One d-c output voltage is rectified and applied in a feedback connection to the first regulator transistor, which is also tied to a Zener diode, functioning as a constant voltage-drop device. Setting of the output-voltage level is accomplished by means of the variable resistance, which taps off a voltage for amplification in the subsequent transistor stages. This amplified signal is combined with the battery-source voltage in the common emitter circuit of the switching transistors. Thus, any variation in output current drain is reflected through the common transformer winding to vary the feedback voltage in such a direction as to offset the accompanying variation in output voltage. Similarly, a fall or rise of the source-battery voltage during low specific gravity periods or high charging-rate intervals cannot prevent the circuit from maintaining the point of output voltage equilibrium selected by the variable resistance setting.

Circuit values are as follows:

Input voltage:	21 to 28 volts dc
Output power:	300 volts dc at 10 ma
Aux output No. 1:	35 volts ac at 1.0 amp
Aux output No. 2:	26 volts ac at 0.5 amp

Table 1-19—Multiple Output, High-Power, Transistorized Power Supply, Specification Data

Nominal voltage (vdc)	Load current (amp)	Regulation	Stability	Ripple	Output impedance	
		From 10% load to 100% load (%)	For a 24-hr period (%)	Peak to peak (mv)	0-200 kc (ohms)	200 kc to 1 Mc (ohms)
Central						
+28	2.5	±5	±5	280	1	5
+1.5	1.75	±10	±5	15	1	5
-6	0.100 - 1.500	±5	±5	60	1	5
-7.5	1.0	±10 of 1.5 volts tracking 6 volts supply	±5	75	1	5
-28	5.0	±5	±5	280	1	5
+300	0.250	±0.75	±0.75	20	1	3
-150	0.600	±0.75	±0.75	20	1	3
-150	2.0	±0.75	±0.75	20	1	3
Standby						
+28	1.0	±5	±5	280	2	5
+1.5	0.5	±10	±5	15	1	5
-6	0.4	±5	±5	60	2	5
-7.5	0.5	±10 of 1.5 volts tracking 6 volts supply	±5	75	1	5
-28	2.0	±5	±5	280	2	5
+300	0.100	±0.75	±0.75	20	2	5
-150	0.350	±0.75	±0.75	20	3	5
+150	0.600	±0.75	±0.75	30	3	5

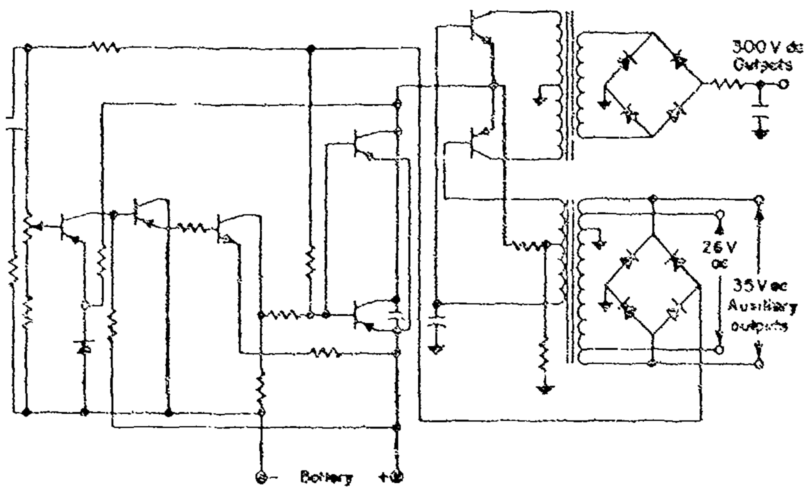


Fig. 1-. Regulated transistorized power supply having regulation less than 1 percent for 20-percent d-c load change and 50-percent a-c load change over temperature range from -55 to 85 C.

MAINTENANCE

Maintenance requirements are expected ultimately to consist of transistor replacement only. Germanium transistors currently cost approximately $2.50 each, and it is anticipated that further refinements in the production process will also reduce this amount.

Preventive maintenance measures are aimed primarily at preventing excessive transistor junction temperature. This is necessary since transistor failure occurs abruptly and is caused in nearly all cases by excessive transistor junction temperature. A slight temperature rise above the critical upper limit causes an increased current flow; this in turn causes more heat at the transistor junction causing a further increase in current flow. The heat and current flow avalanche in a very brief interval to destroy the transistor. Transistors must be replaced in matched pairs to accommodate the required condition of circuit balance necessary to proper operation in converter applications. Matching within 5 to 10 percent of impedance values in each direction is necessary.

APPLICATION PRECAUTION

When the output ripple is difficult to filter, and may cause adverse effect upon adjacent circuitry, select a transistorized power supply that utilizes an operating frequency such that ripple can be allocated to a nonobjectionable part of the associated system's bandpass. The ripple frequency occurs at twice the oscillator frequency.

COMPARABLE TECHNIQUES

The power conversion techniques utilizing the dynamotor and the vibrator power supply are compared with the transistorized power supply in Table 1-9 in terms of their required inputs, available outputs, and dynamic operating characteristics. It must be realized that the quantities associated with the vibrator power supply and the dynamotor have been stabilized over years of extensive use while the capabilities of the transistorized power supply are constantly being improved.

REFERENCES

1. Smyth, R. R., "Development of Power Transistor Circuitry," Technical Operations Inc., Signal Corps Project No. 162B, 14 May 1956.
2. "The Status of Power Transistors for Use in DC-to-DC Converters," Technical Memorandum 1819, Signal Corps Engineering Laboratories, Fort Monmouth, New Jersey, 15 August 1956.

BIBLIOGRAPHY

Bright, R. L., and A. P. Kruper, "Transistor Choppers for Stable D-C Amplifiers," Electronics, April 1955.

Bright, R. L., C. F. Pitman, Jr., and George H. Royer, "Transistors as On-Off Switches in Saturable-Core Circuits," Electrical Manufacturing, December 1955.

Ebers, J. J., and J. L. Moll, "Large Signal Behavior of Junction Transistors," Proceedings of the IRE, December 1954.

Keller, J. Walter, Jr., "Regulated Transistor Power Supply Design," Electronics, November 1956.

Lyons, Lambert F., "Magnetic Regulation Transistor Power Supply," AIEE Communication and Electronics, January 1957.

Pearlman, Alan R., "Transistor Power Supply for Geiger Counters," Electronics, August 1954.

"Switching Transistors Used as a Substitute for Mechanical Low-Level Choppers," AIEE Communication and Electronics, March 1955.

"Transistors as Switches," report issued by the Applied Physics Laboratory, Johns Hopkins University APL/JHU CF-2353, Silver Springs, Maryland, 11 March 1955.

PRIMARY BATTERIES

Although much electronic and electrical equipment is designed to operate directly from an a-c source, there are still numerous applications for battery power supplies. Battery power is most useful where a high concentration of energy per pound is required, where independence of individual equipment from a central power source is necessary, and where an unattended power source and renewal by unskilled operators is required.

Many primary batteries of different combinations of size, shape, weight, and electrical characteristics are available for use in military equipment. For this reason one of the

major problems of the design engineer is to select the correct battery or cell for a particular application.

BATTERY CLASSIFICATION BY USAGE

Primary batteries for use in electronic equipment are generally classified according to their intended use. Those used to heat the filaments of electron tubes are referred to as "A" supplies. They are generally low-voltage batteries with high-current capabilities. These batteries also find applications as power sources for flashlights, boosters, and telephone circuits.

Primary batteries used to supply screen and plate currents for electron tubes are called "B" batteries. They are capable of supplying low steady currents at relatively high voltages. These batteries also find applications as high-voltage sources.

Batteries supplying voltage to control grids in electron tubes are known as "C" batteries. In test sets, "C" batteries are also used to supply power for the ohmmeter.

Primary batteries are also used in portable or emergency lighting, either as self-contained power supplies or as standby power when the normal supply fails. Although some of the batteries previously mentioned may be used for lighting purposes, they are used principally in electronic equipment because of their small size. The larger cells and batteries are used for lanterns.

Other applications for primary batteries are found as power sources for mechanical devices such as step-by-step motors, servos, and selsyns. Normally these uses are somewhat limited since batteries become cumbersome as the voltage and current requirements increase. In telephone service, dry batteries are used as power supplies for talking and ringing circuits, operation of transmitters on magneto switchboards, intercommunicating systems, and interrupters.

PRIMARY BATTERY TYPES

Batteries used in the military services fall into three broad classifications: (1) conventional dry batteries which are ready to use when purchased, and which are employed in great numbers in military and civilian applications, (2) low-temperature batteries, and (3) reserve batteries which are not ready to use when purchased but become so when the user activates them in some way.

Dry Cells. The common dry battery, typified by the No. 6 dry cell and the radio "B" battery, is the oldest type now in common use and is employed in the greatest numbers. Its basic origin was the Leclanché cell and its constituents are the familiar zinc case and its carbon-rod cathode surrounded by the electrolyte.

Other types of primary cells employ mercury, zinc-silver chloride, magnesium-silver chloride, zinc-silver peroxide, and numerous other chemical combinations.

Low-temperature cells are physically similar to and interchangeable with conventional cells, with the exception that they have better performance characteristics at low temperatures. The low-temperature cells have electrolytes composed of solutions of ammonium chloride, lithium chloride, or similar solutions that will not freeze at temperatures above -40 C.

GLOSSARY

Primary cell. A cell that is a source of electrical energy from a chemical reaction which is not reversible because of the chemical condition or physical state of the electrodes after discharge. A dry cell is a primary cell with an electrolyte in the form of a paste or jelly confined to permit ease of handling and use in equipment or areas where the escape of corrosive chemicals cannot be tolerated.

Electrolyte. The solid paste, or liquid used between the electrodes in a cell which provides ions for transfer of charge at the electrodes.

Electromotive force. The total electric potential of a cell due to its parts. It is produced chiefly by the difference in potential between the electrode materials. The terminal voltage depends on the electrode material, the internal resistance, and degree of polarization.

Polarization. The change in electromotive force of a cell caused by chemical changes in the cell while current is flowing through it. Polarization reduces the terminal voltage of a cell.

Battery. A number of cells connected together to obtain the required voltages or capacities and packaged in a container. It is customary to apply this term to a single cell also.

Capacity. The product of the average current drawn from a cell or battery and the time during which the current is drawn before the cell or battery voltage drops below a useful level. It is usually expressed in ampere-h[illegible]

The most common reserve-type or delayed action cells have the same physical dimensions as conventional cells but differ in the electrolyte. Reserve cells are shipped and stored in a dry state. Water must be added before putting the cell into service. This cell finds application where long storage conditions are anticipated prior to use. The batteries can be designed so that the electrolyte may be admitted to the cells from a separate c tainer; or they may have an internal container for electrolyte, which is then introduced by means of compressed gas. Normally, the battery should be used where it will be discharged within a reasonable time after activation.

Mercury Cells

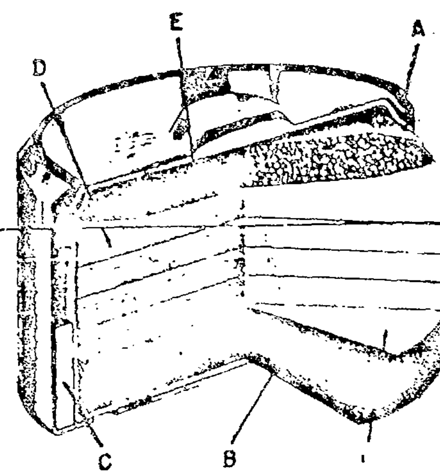
Mercury-type di y batteries are made up of cells consisting of four basic components. These cells, commonly referred to as "RM" cells, have an anode of high-purity zinc, a positive electrode composed of mercuric oxide which also acts as a depolarizer, and an electrolyte of either potassium or sodium hydroxide. In contrast to the common dry cells, the cell container is a steel can that does not take part in the reaction providing the electrical energy. The construction of mercury cells is sho m in Fig. 1-87.

Th vice capacity of batteries structed of "RM" cells differs from tha available from ordinary dry cells. On a unit volume basis, the mercury cell has several times greater capacity. Figure 1-88 compares the terminal voltages of an "RM" battery and a Leclanché battery versus working life hours. The voltage or current discharge of "RM" cells is relatively steady. This characteristic, the lack of requirement for rest periods during operation, and the low internal impedance make these cells well suited for use in communications equipments, transistor devices, and meteorological instruments.

Mercury batteries have good high-temperature characteristics as may be seen in Fig. 1-89. The capacity of the mercury cell is much greater than a dry cell at room temperatures, but as temperatures decrease the efficiency drops, and below 20 F the dry cell gives better performance.

Zinc-Silver Chloride Cells

These cells are used in applications of very low current drain. They have a cathode of silver chloride, an anode of pure zinc, and an electrolyte of ammonium chloride in the form of a jelly. They have a high internal resistance.



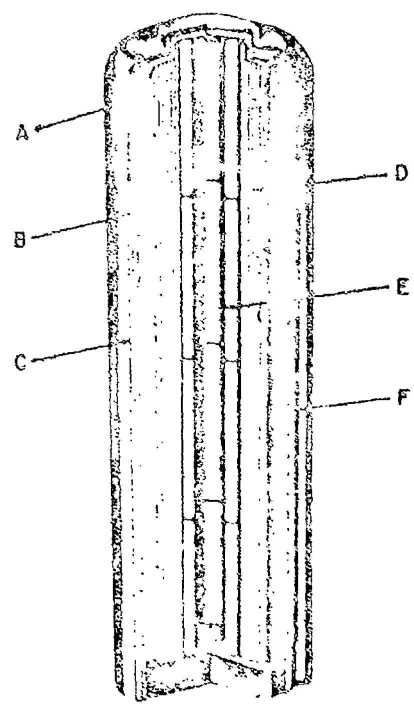


Fig. 1-87. Construction of mercury cells. (A) Flat type, pressed powder anode (B) Cylindrical type, pressed powder anode. (P. R. Mallory Co.)

Magnesium-Silver Chloride Water Activated Cells

These cells have a high power-to-weight ratio and are excellent for "one-shot" applications where discharge curves must be rel-

atively flat throughout use. Each cell has a nominal voltage of 1.5 volts. Like other water activated dry cells, these are shipped and stored dry.

Zinc-Silver Peroxide Cells

Zinc-silver peroxide reserve primary batteries are of considerable interest for applications where low voltage-temperature coefficient, remote activation, and long shelf life are required. The electrolyte is potassium hydroxide. It is stored in a separate compartment or container and introduced at the time of putting the battery into service. The cells have nominal voltage of approximately 1.4 volts. Batteries of this type can produce a considerable amount of energy in a relatively short time, for example, 30 watt-hours per pound when discharged to exhaustion in 15 minutes. This battery lends itself to missile and other applications where it is desirable to have battery supplies that do not require internal heating or charging facilities to operate.

SPECIFICATIONS AND STANDARDS

Most dry batteries that are required for military use are procured under military specifications that normally contain information defining the battery construction and its physical and electrical characteristics, but not its electrical capacity in ampere-hours or its expected life. The reason for this omission is that the battery's use, materials of construction, and size have a great influence on its capacity.

Most battery specifications are procurement documents. Although design information may be contained in them, it is not of a nature that can or should be used in selecting batteries for a specific application.

MIL-B-18B, Batteries, Dry

Military Specification MIL-B-18B contains basic descriptions including electrical and mechanical characteristics of Leclanché, mercury, and low-temperature type dry batteries. Since this specification covers the greater share of dry cells and batteries used in military applications, it will be discussed in detail.

Batteries and cells procured under this specification are identified as follows:

BA-	/U
Component	Type Number

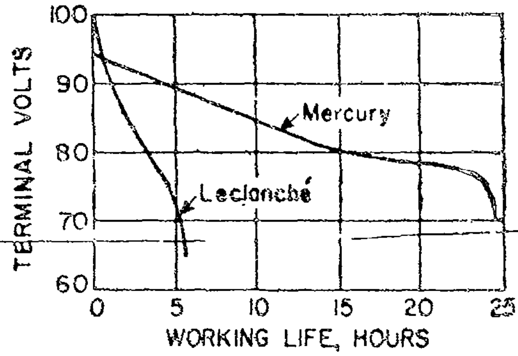


Fig. 1-88. Effect of service life on terminal voltages of Leclanché-type and mercury cell batteries.

1. Component - Dry batteries are identified by the two-letter symbol BA-.

2. Type number - The battery type number identifies the type of cells of which the battery is composed.

a. Leclanché cells - Batteries composed of Leclanché-type cells are identified by the type numbers from 1 to 999 inclusive. For example, the basic type number would consist of one, two, or three digits: BA-2, BA-23, and BA-230/U with certain exceptions: BA-252/U, BA-245/U, BA-253/U, and BA-256/AM, which are procured according to other specifications.

b. Mercury cells - Batteries composed of mercury cells are identified by the addition of "1000," and a "/U" to the basic battery type number. If the basic type number already bears the "U" nomenclature, it is not added a second time. For example, when batteries

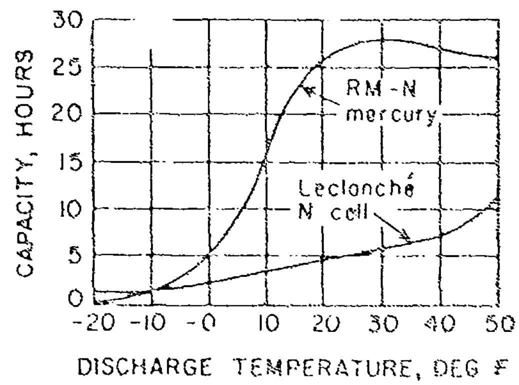


Fig. 1-89. Comparison of capacity at various temperatures of common dry N cell and RM-N mercury replacement cell when discharged on a BA-38 drain.

BA-2, BA-30, and BA-210/U are assembled with mercury cells, they are identified as BA-1002/U, BA-1030/U, and 1210/U respectively. Batteries having corresponding numbers are physically identical whether they are constructed of Leclanché or mercury cells. The electrical characteristics will differ somewhat, as shown in the section on electrical characteristics.

c. Cells designed for low-temperature operation are identified by an addition of "2000" and a "/U" (when the "U" does not exist as part of the basic number) to the battery number. For example, when batteries BA-2, BA-30, and BA-402/U are assembled with cells designed for low temperature they are identified as BA-2002/U, BA-2030/U, and BA-2402/U.

Batteries made according to this specification cover a wide range of voltages and are available in a large variety of sizes and shapes having various types of terminals. For detailed characteristics, the reader is referred to the specification and its individual specification sheets. To facilitate referring to specification sheets, Tables I and II in the Appendix list the various batteries according to their voltages.

MIL-B-25356(USAF), Battery, Dry, Special Purpose

This specification covers a dry battery having a nominal voltage of 13.4 volts and a tap at 1.34 volts. The current ratings are 200 ma-hours and 3600 ma-hours respectively. The battery has wire leads and is composed of mercury cells.

MIL-B-10154A, Batteries, Primary, Water Activated (Dunk Type)

This specification covers primary batteries intended for use where high capacity per unit of weight and extremely long shelf life are the prime considerations. These batteries are inert until immersed in water for activation. The type designation is somewhat similar to that in MIL-B-18B. It is composed of BA to indicate primary battery, a type number (253, 259, 323, 318) to indicate a specific battery, and an installation indicator of one or more letters to show the equipment with which the battery is associated (AM, airborne meteorological equipment; U, general utility which includes two or more general installation classes such as airborne, shipboard, or ground). An example of a complete designation is BA-259/AM.

MIL-B-13136(SigC), Battery, Dry, (BA-245/U and BA-2245/U)

MIL-B-13136(SigC) covers single cell dry batteries that have a chloride electrolyte and a nominal voltage of 1 volt. They are intended for use as the power source for blasting circuit galvanometers. BA-245/U is used in temperate and tropical zones; BA-2245/U is used in arctic zones.

MIL-B-7156B(ASG), Batteries, High Capacity, Special Single Discharge, Aircraft Use

This specification covers 7.5- and 10.5-volt special purpose batteries used in military aircraft. These batteries are intended for single discharge service under severe climatic conditions. The cells are permanently sealed except for filter openings.

Specification MIL-B-13172(Navy). This specification covers the limits, acceptable quality levels, sampling procedures, and evaluation of performance on capacity tests for Navy dry batteries. In Navy procurement contracts, provisions of this specification supersede requirements in MIL-B-18. Other characteristics of batteries are the same as in MIL-B-18.

W-B-101c Batteries and Dry Cells

This is a Federal Specification for dry cells and batteries. It includes the following types: No. 6 general purpose dry cells, No. 6 and 8 telephone dry cells, assembled batteries of No. 6 general purpose cells, flashlight cells and batteries, and radio "B" and "C" batteries.

Two other special purpose batteries are covered by MIL-B-12079(SigC), vest-type dry batteries, and MIL-B-7913(Aer), 150-volt standby dry "B" batteries.

National Bureau of Standards Circular 559

Commercial dry cells and batteries may be designed to National Bureau of Standards Circular 559, which covers general purpose, industrial, telephone, flashlight, "A," "B," "C" radio, and A/B battery packs. The physical characteristics and electrical tests specified provide for uniformity and acceptable quality of the batteries made for commercial use.

DRY BATTERY CONSTRUCTION

Dry cells have four major components: anode, cathode, electrolyte, and a depolarizing agent.

The anode or negative electrode is composed of high-purity zinc (over 99.5 percent pure). In cylindrical cells, it serves as the cell container and is generally provided with some type of terminal, depending upon its intended application.

The purity of the zinc is important since small particles of impurities such as iron, copper, cadmium and lead set up many small "local cells" on the inside surface of the zinc can. This results in the zinc being continuously eaten away whether the cell is in use or not. The small currents eventually weaken the cell and waste the cell capacity. Figure 1-90 diagrammatically illustrates this process. The magnified particle is of iron; the local current flow is from the zinc to the iron to the zinc. This is generally referred to as local action.

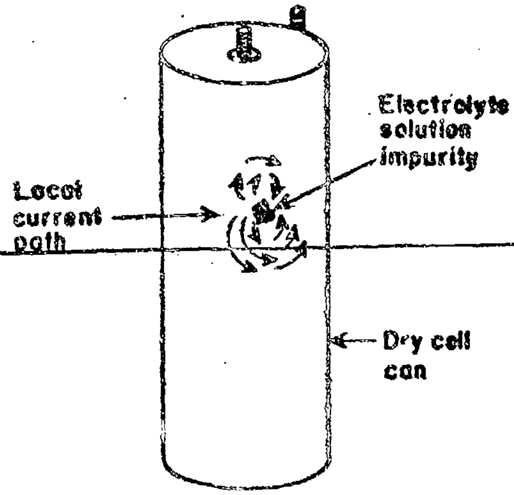


Fig. 1-90. Illustration of local action.

The cathode or positive electrode is a carbon rod made by mixing coke or graphite with pitch and heat treating the mixture to make the electrode conductive. The rod is somewhat porous to permit gas to escape and generally has a rough surface to make good contact with the depolarizer.

The depolarizing agent is a homogeneous mixture of approximately 90 parts of manganese dioxide and 10 parts of carbon black moistened with ammonium chloride. The physical properties of the mix vary with the intended application and method of manufacture.

The electrolyte is in the form of a jelly consisting of ammonium chloride and zinc usually mixed with flour. Inhibitors such as chromic salts are added to prevent corrosion of the zinc can.

Flat-type cells, Fig. 1-91, consist of the same four parts as the cylindrical cells; however, the flat cells are in slab form and sealed by a plastic envelope and sealing wax to prevent loss of moisture.

Physical and Mechanical Considerations

Primary cells are available in various sizes, weights, and shapes. Table 1-20 includes the sizes and shapes of both dry cells and mercury cells. Batteries constructed from these cells are usually square or rectangular. For exact shapes and dimensions, the applicable military specification sheet should be consulted.

The cell seal is either a sealing wax or an insulated metal enclosure. It is designed to protect the contents of the cell and to prevent loss of moisture. Most sealing waxes contain rosin and some other material to lend mechanical strength. Occasionally, asphalt or pitch is used in multicell batteries. Since these materials are soft they are generally surrounded by a cardboard container. Sometimes a metal seal is used to form an airtight enclosure.

Terminals

Terminals provide a positive means of making external electrical connections to the battery and come in many styles as shown in Fig. 1-92. In addition, many batteries have center taps requiring multiple terminals on the battery.

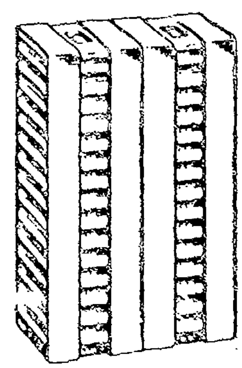


Fig. 1-91. Flat common dry cell.

Table 1-20.—Dimensions and Weights of Standard Dry Cells from MIL-B-18B of July 1, 1953

Cell designation	Nominal dimensions (in.)				Approximate weight (lb)
	Diameter	Length	Width	Thickness	
Cylindrical Leclanché Cells					
6	2-1/2	6	--	--	2.2
J	1-1/4	3-7/8	--	--	0.6
G	1-1/4	4	--	--	0.4
F	1-1/4	3-7/16	--	--	0.35
E	1-1/4	2-7/8	--	--	0.28
D	1-1/4	2-1/4	--	--	0.22
CD	1	3-3/16	--	--	0.20
C	15/16	1-13/16	--	--	0.10
B	3/4	2-1/8	--	--	0.077
BR	3/4	1-1/2	--	--	0.046
A	3/8	1-7/8	--	--	0.046
AA	17/32	1-7/8	--	--	0.033
R	17/32	1-5/16	--	--	0.023
P	17/32	1	--	--	0.018
M	17/32	3/4	--	--	0.013
N	7/16	1-1/16	--	--	0.012
NS	7/16	3/4	--	--	0.009
X	17/32	1/2	--	--	0.006
FL-10	--	2-3/8	1-25/32	0.41	--
FL-9	--	1-11/16	1-11/16	0.31	--
FL-8	--	1-11/16	1-11/16	0.25	--
FL-7	--	1-45/64	1-45/64	0.22	--
FL-6	--	1-1/4	1-1/4	0.15	--
FL-5	--	1-1/4	1-1/4	0.14	--
FL-4	--	1-1/4	27/32	0.21	--
FL-3	--	1-1/4	27/32	0.18	--
FL-2	--	15/16	17/32	0.11	--
FL-1	--	9/16	9/16	0.12	--
Cylindrical Mercury Cells					
R-4R	1.188	0.541	--	--	0.031
R-3R	0.972	0.523	--	--	0.032
R-2R	0.819	0.618	--	--	0.035
R-1R	0.605	0.460	--	--	0.018

Flat-surface terminals are specified on some batteries. The negative terminal is a flat plate or the bottom of the cell can; the positive terminal is a plate with a raised center cylindrical portion.

When flexible wire leads are used, they are color coded as follows: positive, red; negative, black; color of tape as specified on individual battery specification sheet. Unless otherwise specified the wire leads are generally 6-1/2 inches in length. The free ends are bared for 1/2 inch in length.

Some batteries are designed with snap-on terminals. These terminals are made in two parts: a socket that is the negative terminal and a stud for the positive terminal. Other dry batteries are designed with flat spring or coil and flat spring terminals. Spring-clip terminals are made of spring brass or phosphor bronze. The clips will accommodate commonly used radio hookup wire. Stud and nut terminals are usually made of brass. In some cases the nut is made of insulating material containing a brass insert. Socket-type terminals have contact portions made of phosphor bronze. Individual specification sheets should be consulted for spacing and tolerances of socket terminals.

CELL CHEMISTRY

The chemical reaction consists primarily of oxidation of the zinc container and reduction of manganese dioxide. An extensive discussion of the ways in which this transformation of energy may take place is given in the literature. (1)

ELECTRICAL CHARACTERISTICS

The electrical characteristics of dry batteries are dependent upon the materials in the

electrodes, cell size, connected load, temperature, and other parameters which will be discussed later.

Voltage

The open circuit voltage of a primary cell depends upon the electrode materials. The common dry cell has a nominal voltage of 1.5 volts; mercury cells, 1.34 volts. The nominal voltage does not depend upon cell size. Batteries BA-23, BA-30, BA-42, and BA-58, shown in Fig. 1-93, all have a nominal voltage of 1.5 volts, but their capacities are different.

The working voltage of a cell is dependent upon the circuit in which the cell is used. It is affected by the cell's internal resistance and also by the current drain. Desired battery voltages and current capacities are obtained by connecting cells in series, parallel, or a combination of both.

Internal Resistance

The internal resistance is dependent upon the amount of charge remaining in the unit, the temperature at which it is operated, and to some degree on the current drain. In theory, when the internal resistance of a battery is equal to the load resistance, the battery will deliver maximum power to the load. Since the internal resistance of a battery varies with service, the condition of maximum power delivery to a load is very rarely encountered in practice.

Although the internal resistance of a cell increases during use, it is not much cause for concern to the designer as long as the battery terminal voltage is higher than the end test voltage in the applicable specification. However, if the life of the battery is extended beyond the limit specified by the end test voltage, the possible effects of this increase in resistance should be considered by the designer.

Life

The life of a battery depends upon its ampere-hour rating, its connected load, and its duty cycle. The ampere-hour capacities of

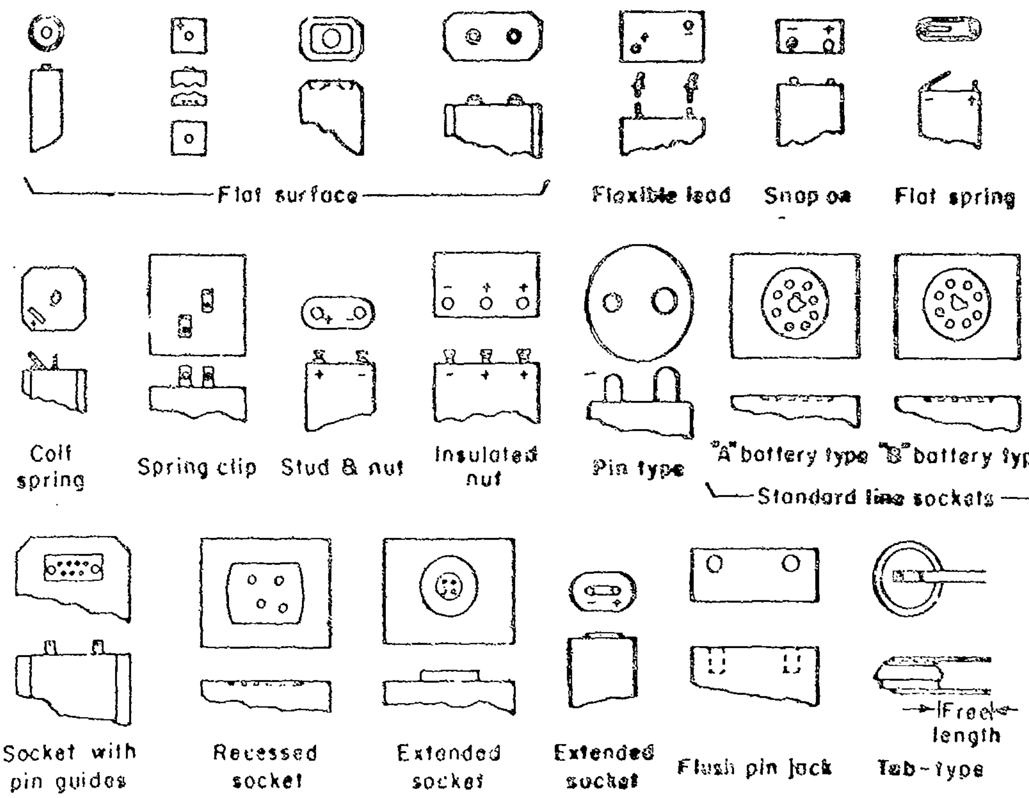


Fig. 1-92. Terminals available for use with MIL batteries. (From MIL Dry Battery Chart prepared by Power Sources Branch, U. S. Army Signal Engineering Laboratories, April, 1956.)

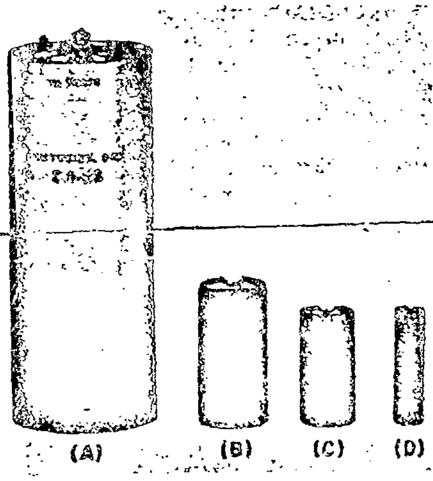


Fig. 1-93. Four common dry cells, differing in size and ampere-hour rating, each having nominal voltage of 1.5 volts.

batteries usually increase as the physical sizes of the batteries increase. Batteries having different physical sizes and ampere-hour ratings are shown in Fig. 1-93.

In addition to varying with the size of the cell, the ampere-hour rating of similar cells varies among manufacturers because of the different types of materials used in cell construction: either "synthetic ore" or "natural ore." Generally, cells made with synthetic ore have higher ampere-hour capacities than those made with natural ore. Some discharge curves for size B cells of different manufacturers are shown in Fig. 1-94.

Connected Load or Current Drain. Current drain has a significant effect on battery life.

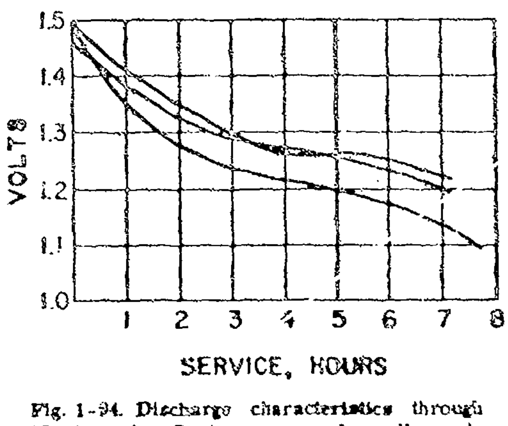


Fig. 1-94. Discharge characteristics through 25 ohms for B size common dry cells made by different manufacturers.

The series of curves in Fig. 1-95 illustrate how increased battery life may be obtained by reducing the current drain.

Since it is evident that the life of a normal battery is relatively short at high-current drains, special batteries, such as the zinc-silver-peroxide-type, are used in applications that require a heavy continuous discharge. The current that can be supplied by any battery will decline gradually because of the accumulation of waste products within the cells.

When a continuous load is placed on a dry battery, the depolarizer does not have a chance to function properly. Hydrogen accumulates rapidly at the electrode, causing the working voltage to decrease. If current is withdrawn within battery capabilities, waste products of the chemical reaction have an opportunity to diffuse within the cell and working voltages can be maintained. If the withdrawal of energy

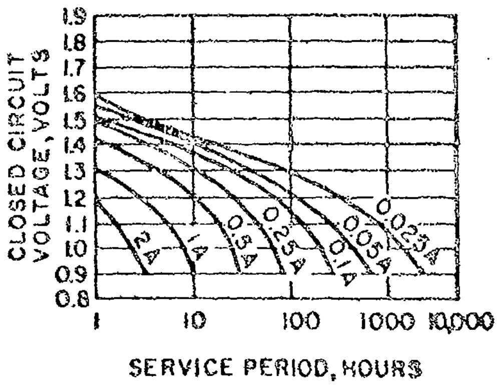


Fig. 1-95. Life of a BA-35 battery as function of current drain.

is at a low rate, the shelf life of the battery enters into the overall life picture. In this case the time required to exhaust the cell is so long that internal deterioration, inherent in dry batteries, takes place resulting in a corresponding reduction in cell energy.

To avoid insufficient or excessive battery capacity, individual specification sheets and battery information should be followed when specifying batteries for equipment.

Duty Cycle. Operating schedules are an important consideration in battery life since most batteries are intended for intermittent operation. Figure 1-96 shows the effect of two different duty cycles on the life of a BA-30 battery. To maintain a proper discharge rate,

the electrolyte in each cell must be free to circulate between the electrodes in the cell. Since the rate of consumption of the electrolyte is directly proportional to the discharge current, the electrolyte is rapidly used up at high discharge rates. However, if the battery is used intermittently, as most batteries are, the electrolyte continues to diffuse through the battery during the open circuit period of operation, and an additional discharge at the same rate can be obtained until the end-end voltage is reached.

Temperature. Operating temperatures have a marked effect on dry battery operation. This effect varies with regard to battery type, size, and degree of exposure. Conventional dry batteries are not adversely affected by temperatures from 70 to 120 F if the operating period at the higher temperature is not excessive. The operating capabilities decrease as temperature drops. As the operating temperature approaches 0 F, the capacity will be only 60 to 80 percent of normal capacity. The cells will become practically inoperative when reaching -20 F.

Low-temperature dry batteries perform much more satisfactorily than conventional batteries at low temperatures. For example, at lower operating temperatures, the capacity of low-temperature batteries also decreases but at a much lower rate. At -40 F, these batteries provide 10 to 20 percent of their normal capacity. Low-temperature batteries depreciate much faster at normal temperatures and should be used only for low-temperature applications.

A mercury battery's capacity at normal operating temperatures and above is about equal to or slightly greater than its capacity at 70 F. At temperatures below normal, the capacity decreases with temperature. Below 0 F very little capacity remains. The variation in terminal voltage of mercury cells with temperature is shown in Fig. 1-97.

Magnesium-silver chloride batteries experience little effect on their capacities at operating temperatures ranging from -40 to 120 F.

Zinc-silver chloride batteries are adversely affected by abnormal temperatures. Above 70 F the batteries deteriorate; below 70 F the capacity drops as temperature decreases. At -40 F the battery will have practically no capacity.

Where equipment is intended primarily for operating in cold climates, the designer should

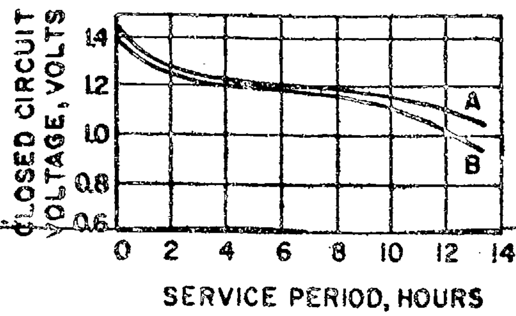


Fig. 1-96. Effect of duty cycle on life of a BA-30 battery.

consider giving the battery some protection from the cold. The battery compartment can be insulated; this will help retain internal battery heat. The battery location can be arranged to take advantage of any internal heat generated by the other components. In cases where alternating current is available, it may be passed through the battery to heat it. Blocking capacitors are necessary to prevent discharging the battery. External heat should be used with great care, since battery components are easily damaged by overheating.

Energy-Weight Ratio

Applications engineers are faced many times with the necessity of selecting a power source where weight is of prime importance. Figure 1-98 indicates the watt-hours per pound avail-

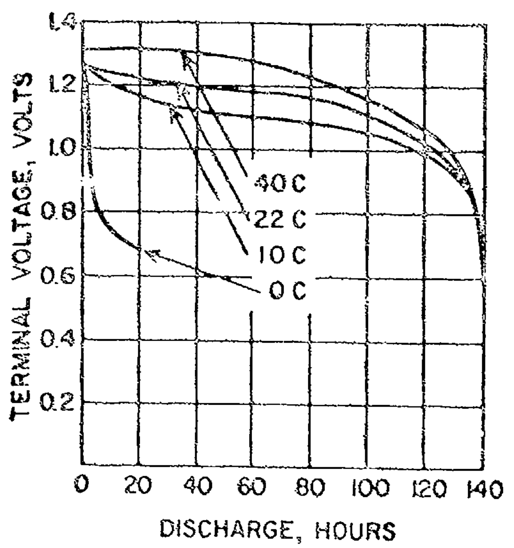


Fig. 1-97. Terminal voltage of a mercury cell as a function of temperature and time of current drain.

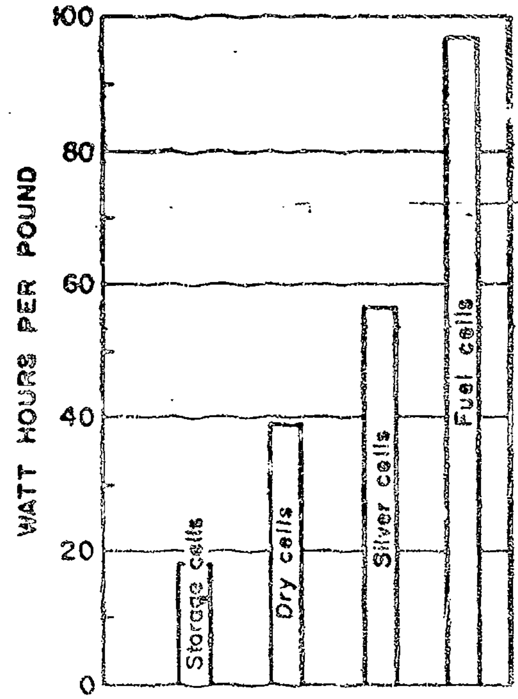


Fig. 1-98. Energy-weight ratio of various cells.

able from various battery types. Primary and secondary types are considered in this graph. Fuel cells, briefly discussed in the section "Trends and Developments," are included for comparison purposes even though practical fuel cells are not available.

ENVIRONMENTAL EFFECTS

Batteries, like all other components, are affected by environments in which they operate, or to which they are exposed. The paragraphs that follow indicate what the designer may expect of batteries under different environmental conditions.

Temperature

Rapidly changing temperatures do not affect dry cells unless the change is great and the length of exposure is long. The internal temperature of cells lags behind external temperature changes, particularly if the cells are in equipment. Temperature changes that cause internal temperatures to fluctuate will cause changes in the electrical characteristics as noted under Life.

Pressure

Dry batteries are designed for operation at normal atmospheric pressures. With the exception of certain specially designed batteries, it is necessary to protect batteries from large changes in pressure by sealing in cans. A decrease of pressure may cause the loss of electrolyte and limit current producing abilities. Mercury cells are generally enclosed in steel containers making them resistant to increased pressures. Most Leclanché and mercury cells are vented to permit the escape of gases that develop from chemical reactions. This will permit the diffusion and escape of electrolyte at extreme altitudes.

As requirements for operation at high altitudes increase, batteries capable of operating at reduced pressures should be used, or else a pressurized container for the battery should be provided. In either event, the pressure must not be permitted to decrease to the extent that the electrolyte will boil.

Mercury cells tested at reduced pressures equivalent to altitudes greater than 50 miles showed no reduction in open circuit voltage. The loss of weight that occurred when mercury cells were exposed to high altitudes is shown in Fig. 1-99.

The existence of "hot spots" in dry batteries should be avoided. Localized heat will cause melting of waxes, pitch, and tars; and increase the possibility of internal short circuits developing or the cell container being destroyed. In addition, at high temperatures, cell activity is greater and deterioration may occur faster.

Moisture and Fungus

These conditions are destructive to dry batteries. Normally, batteries are shipped and stored in packages designed to protect the battery from these destructive elements, and the main problem the designer will have to

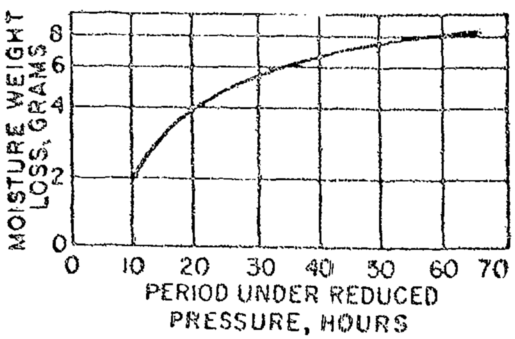


Fig. 1-99. Weight loss of mercury cells when exposed to a pressure equivalent to an altitude of 54 miles.

contend with is in actual use. Since batteries contain many materials that are fungus nutrients and will not withstand moisture, they need protection in applications where these conditions exist. This can be done by treatment with a wax impregnated with a fungicide. In cases where severe conditions are anticipated, batteries constructed with steel cans should be specified. Batteries are normally given a submersion test to determine if the case will fall apart. This should in no way imply use in such conditions. If it is necessary to use a battery in an underwater application it must be enclosed in a metal container and have its terminals protected.

Nuclear Radiation

Generally, it can be stated that some deterioration will be experienced by dry cells when exposed to nuclear radiation, but in most cases this would only shorten cell life. The terminal voltage of the BA-30 (1.5-volt cell) was found to decrease approximately 5 percent after exposure in a reactor to an integrated dosage of 4 times 10^{11} Roentgens/cm^2/sec. The internal resistance doubled.

Vibration and Shock

When cells are exposed to these conditions, their seals may be damaged and internal cell connections opened. Battery manufacturers, by use of potting compounds, make batteries that meet shock and vibration requirements in military specifications. Individual specifications and specification sheets should be consulted to determine these requirements. The effect of vibration on the output voltage of a mercury cell is shown in Fig. 1-100.

HINTS FOR RELIABILITY

To achieve maximum reliability consistent with the equipment requirements, battery capacity should be as large as the equipment requires and as weight and space will permit. It is better to select batteries with cells connected in series-parallel rather than those with cells all in series. It is wise to select the simplest battery available since reliability and simplicity go together. In cases where extreme reliability is required, it may be advisable to consider a secondary battery since this will permit a certain amount of testing. The battery can be discharged and charged giving an indication of the expected performance.

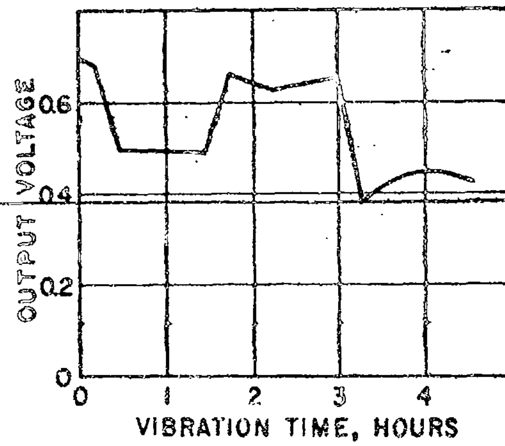


Fig. 1-100. Effect of vibration (0 to 2000 cps) on the output voltage of a mercury cell under load.

TRENDS AND DEVELOPMENTS

"Atomic" Batteries. Nuclear or radioactive batteries received considerable attention when first announced. These batteries convert nuclear energy directly into electrical energy. Because of their small power output, these cells are limited to applications in the microwatt range. Immediate applications appear most promising in standard-cell circuits as reference voltages and as voltage sources for such devices as Geiger counters and dosimeters.

Fuel Cells. These are new types of voltage-generating chemical devices in which there is a continuous feed of "fuel" (the electrolyte) to the battery, usually in the form of a gas. Although reported early in the 19th century by Davy and Grove, these devices have, with few exceptions, been produced only on a laboratory basis. Cells produced in England have delivered as high as 300 amp per sq ft at 0.79 volt. Fuel cells have the advantage of high efficiencies, 40 percent and above. Efficiencies as high as 60 to 65 percent have been achieved by raising operating temperatures to 200 C and pressures to 600 psi.

Fuel cells vary in construction. A typical one has two porous nickel electrodes in which potassium hydroxide is circulated. The reacting gasses, hydrogen and oxygen, are fed to the cell from opposite sides.

Present work indicates that a practical fuel cell will be developed. It offers promise in military power supplies such as guided missile systems, beacon power supplies, and mobile power plants.

Other Chemical Batteries. Solid electrolyte batteries, with the electrochemical system in a solid form, are produced by several manufacturers. These batteries feature high voltage, small size, long shelf life, and shock and vibration resistance. One of the limitations of this type cell is the relatively low current capabilities. The normal current drains are in the microampere range. The characteristics of this cell make it desirable in applications where high voltages are required with no appreciable current drain.

Magnesium dry batteries have been receiving attention from designers. The BA-270/U is being fabricated from magnesium cells.

Research and development into new forms of batteries is taking place in many directions, and it is highly probable that totally new voltage sources will become available. The improvement in the characteristics of the common dry cell over the past years has been very great and gives an indication of the effectiveness of past research. An excellent summary of the trends will be found in the reference to Hamer. (2)

Solar Batteries. Considerable effort is being made to develop solar batteries into useful sources of power. In effect they are reserve batteries because they cease to provide power in the absence of light.

Bell Telephone Laboratories have developed a semiconductor solar battery which has an open-circuit terminal voltage of 0.6 volt in full sunlight and a voltage of 0.45 volt under a load of 40 ma per sq cm of area. It gives about 50 watts per sq yd of electrode surface at an efficiency of about 6 percent.

A cadmium sulfide solar battery has been developed at Wright Air Development Center which has an open-circuit voltage of 0.45 volt per cell, a short-circuit current of 15 ma per sq cm and an efficiency of about 5 percent.

The future possibilities of these solar batteries is still not too clear.

REFERENCES

1. Vinal, G. W., "Primary Batteries," John Wiley & Sons, Inc., New York 1950.
2. Hamer, Walter J., "Modern Batteries," IRE Transactions on Component Parts, Vol. CP-1, September 1957.

Contents

CHAPTER 2 FUSES AND CIRCUIT BREAKERS

Chapter 2

FUSES AND CIRCUIT BREAKERS

Fuses and circuit breakers are circuit protecting devices. Their primary purpose is to disconnect individual circuits, components, or equipment from a power source when a potentially damaging fault occurs in the unit. This fault may be either a moderate overload or a short circuit which, because of the heating effect of an electric current, can create a fire hazard in the wiring system or damage equipment.

The operation of fuses and circuit breakers is based upon a time element principle; that is, on a short circuit they operate practically instantaneously, but on overloads their operation has a definite time lag that varies inversely with the overload. The general shape of this characteristic is shown in Fig. 2-1. Specific characteristics are shown later in the chapter.

DEFINITIONS

Fuse. A fuse is a protective device containing an element that melts or breaks when the current through it exceeds a specified value for a given time.

Limiter. A limiter is an aircraft fuse with a high melting point. It has characteristics adapted to protecting a system by opening rapidly under heavy fault currents. The high melting point, 960 C in some types, greatly reduces the effect of ambient temperature.

Circuit Breaker. A circuit breaker is an electromagnetic or thermal device that automatically opens an electric circuit in a given time when the current in the circuit reaches a predetermined value.

CIRCUIT INTERRUPTION

The principle of current interruption in a d-c circuit varies from the principle in an a-c circuit. In direct current there is no current zero; therefore, to open a d-c circuit automatically, as a fuse or a circuit breaker operates, the current must be forced to zero by some means. There are two major ways of doing this: (1) either by increasing the arc resistance until the voltage drop across the arc equals the circuit voltage or (2) by decreasing the temperature of the arc and thereby decreasing the ionization in the arc.

Arc resistance is increased either by lengthening the path of the arc or by con-

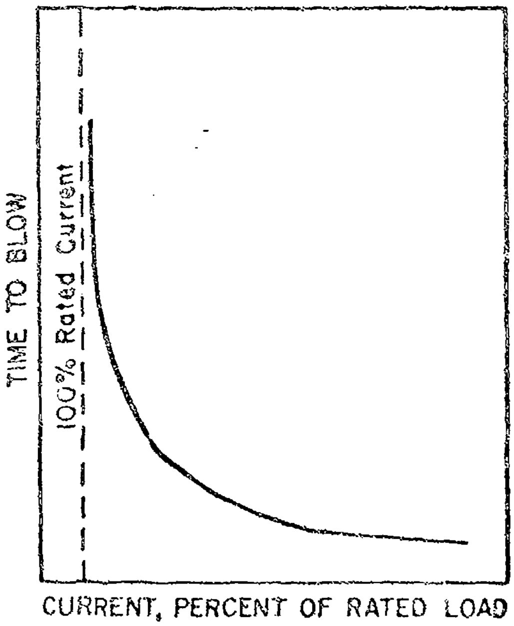


Fig. 2-1. Basic current-time-to-blow characteristic.

stricting the diameter of the arc. It may also be accomplished by a combination of the two.

In the method of circuit interruption that uses the principle of arc temperature reduction, a fusible element, usually silver, surrounded by a filler, usually silica, is enclosed in the protective tubing of a cartridge fuse. When the relation between current and time is such as to melt the fusible element, an arc is formed. The heat from the arc vitrifies the filler. Because the filler removes heat from the arc more rapidly than it is being generated, ionization is reduced and the current falls to zero. When the principle of arc temperature reduction is applied to circuit breakers, a cold blast of air is the temperature reducing medium.

On the other hand, the current in an a-c circuit periodically passes through zero. It is only necessary, therefore, to prevent reignition of the arc after one of these zero points to interrupt the circuit. Because of this, deionization of the arc gap when the current is near zero is very important. The arc will be extinguished when the dielectric strength of the gap permanently exceeds the voltage across the gap that tends to reestablish the flow of current in the circuit.

FUSES

Fuses are the simplest devices known for protecting electric circuits and automatically opening a circuit when an overload or a short circuit occurs. They are made in two major styles: the plug type, which is rated up to 30 amp in circuits where the voltage does not exceed 125 volts to ground; and the cartridge type, which is rated up to 600 amp in circuits up to 600 volts. Cartridge fuses come in two distinct shapes—the ferrule type, which is rated from 0 to 60 amp, and the knife-blade type, which is rated from 61 to 600 amp. Since knife-blade fuses have ratings that are beyond the scope of this chapter, they will not be discussed. General views of the various fuses are shown in Fig. 2-2.

The characteristics of a fuse are built-in and are primarily dependent upon the material, the length and shape of the fusible element, and the arc quenching and arc suppressing techniques incorporated. To a lesser degree, the characteristics of a fuse are dependent upon the body and thermal design. The ambient temperature at which the fuse is used, aging, cyclic fatigue, and fuse current rating in respect to its blow time current, greatly affect these characteristics. Time-to-blow characteristics of a fuse are usually based on an ambient temperature of either 20 or 25 C.

The fusible element is made of a low-melting-point alloy or of aluminum. The resistance of the element when a current is flowing through it causes the temperature of the element to rise. When this rise is high enough above ambient temperature to reach the melting point of the link, the link will volatilize and open the circuit if the resulting arc is self-extinguishing.

The fuses commonly used in electronic equipment and circuits are known as normal lag, quick acting, and time delay. These descriptive names indicate the speed at which the fuses interrupt the current in a circuit. Some representative values are given in Table 2-1, and physical sizes and electrical ratings are shown in Table 2-2.

Fuse Characteristics

All fuses are designed to carry rated load indefinitely and stated overloads for varying periods of time, as shown in Table 2-1. They also have a maximum voltage rating. This is the maximum voltage at which a fuse can permanently interrupt the current in a circuit within a predetermined time.

Normal-Lag Fuses. Normal-lag cartridge fuses are composed of an insulating cylinder surrounding a fusible element that is connected to metal end caps sealing the cylinder. Fuses that have a high interrupting capacity have a powder or sand filler in the cylinder around the fusible element to quench the arc

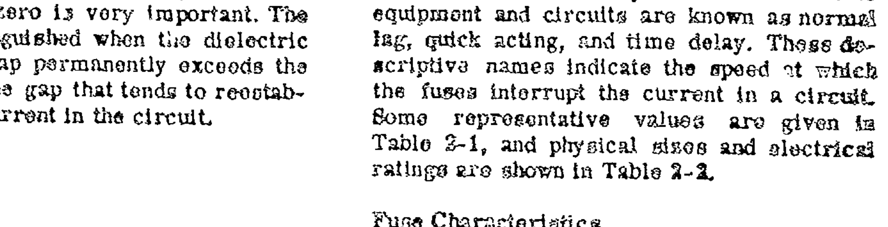


Fig. 2-2. Representative cartridge and plug fuses. (A) Cartridge types. (B) Plug type.

Table 2-1—Blowing Time of Fuses

Type	Percent of rating				
	100	110	135	150	200
Normal lag Quick acting Time delay	— life --	life -- life	0-1 hr -- 0-1 hr	— 0-10 sec --	0-2 min 0-5 sec 5-60 sec

Table 2-2—Physical Sizes and Ratings of Cartridge Fuses

Type	Physical size (inches)	Ratings	
		volts	amp
Normal lag	1-1/2 × 13/32 1-1/4 × 1/4	32, 250 32, 125, 250	1-50 1/16-20
Quick acting	1 × 1/4	32, 125, 250	1/500-8
Time delay	1-1/2 × 13/32 1-1/4 × 1/4	32, 125 32, 125	1-30 1/100-8

that occurs during circuit interruption. As they are used when no special requirements exist, except that equipment and components are to be protected against overloads, normal-lag fuses are the most widely used fuses in electronic equipment. Their current-time-to-blow characteristics are shown in Figs. 2-3 and 2-4.

Quick-Acting Fuses. As their name implies, quick-acting fuses have a shorter time-to-blow than normal-lag fuses for the same overload. They are used where the normal-lag characteristics would not give adequate protection to such items as instruments and delicate equipment that do not have any overload capacity.

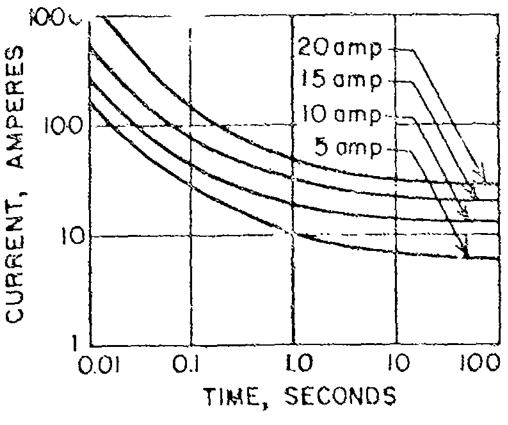


Fig. 2-3. Current-time-to-blow characteristics of normal-lag fuses (32 volts rated).

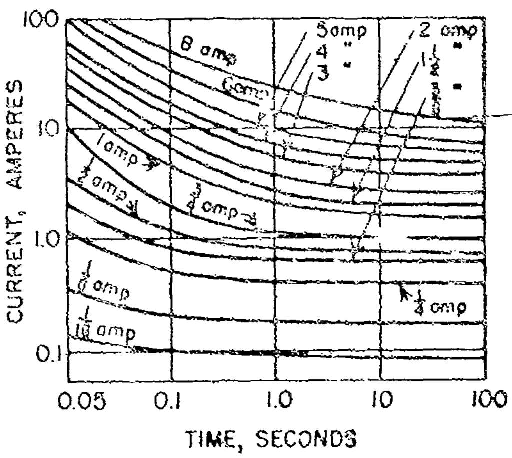


Fig. 2-4. Current-time-to-blow characteristics of normal-lag fuses (250 volts rated).

When quick-acting fuses are used in measuring circuits, their resistance should be taken into account. As indicated in Table 2-4, the resistance values of these fuses vary over a wide range. The values listed in the table should be used as guides only, since the resistance of any fuse will differ from the tabular values because of normal commercial tolerances, the degree of loading of the fuse, and variations between manufacturers.

Time-Delay Fuses. Time-delay fuses are used to protect equipment that takes a high initial current that later drops off to the operating current. Examples of this are the high inrush current compared to the running

Table 2-3— Resistance of Quick Acting Fuses*

Ampere rating	Cold resistance (approx ohms)	Hot resistance (approx ohms)
1/500	2500	3300
1/200	450	770
1/100	150	310
1/32	24	83
1/16	6.6	10.6
1/8	1.6	3.1
1/4	2.9	9.6
3/8	1.9	10.5
1/2	1.9	4.3
3/4	0.78	4.7
1	0.35	0.75
1-1/2	0.10	0.33
2	0.07	0.21

*Supplied by Bussmann Manufacturing Company. Cold resistance obtained on Wheatstone bridge; hot resistance obtained at 100 percent load.

current of an electric motor, or the initial surge current of a capacitor when voltage is first applied. The physical sizes and ratings of these fuses are shown in Table 2-2.

The construction of a time-delay fuse is different from that of either a normal-lag or a quick-acting fuse. Normal-lag and quick-acting fuses have simple elements that melt on overloads, but the time-delay fuse has a compound element composed of a fusible link and a thermal cutout. The fusible link operates only on short circuits or very high overloads, and the thermal cutout functions only on low or moderate overloads. The current-time-to-blow characteristics of this class of fuse are shown in Fig. 2-5. A comparison of relative times to blow, shown in this figure with the times shown in Fig. 2-3, indicates the delay in fuse blowing time that can be obtained by the use of time-delay fuses when the occasion requires.

Aircraft Fuses (Limiters). The fusible element in this type of fuse has a high melting point compared with ordinary fuse elements. These limiters are used in aircraft electric systems up to 120 volts dc, or 120 volts to ground, 400 cycles ac. They have special knife-blade contacts to prevent the use of ordinary fuses in their place. One type of limiter is shown in Fig. 2-6, specifications of three limiters are shown in Table 2-4, and representative current-time-to-blow characteristics are shown in Fig. 2-7. These limiters, rated at from 1 to 100 amp, can protect circuits in which the short-circuit current may reach values as high as 4000 amp.

Vibration-Resistant Fuses. Ordinary cartridge fuses generally have a delicate fusible element that may be damaged when subjected to vibration. Fuses with specially designed elements should be used when they will be exposed to vibration.

One type of fuse has a spring-like formation at one end of the element having wing-like extensions that are twisted 90 degrees and come in contact with the glass wall of the tube to decrease vibration of the element. This type has normal-lag characteristics. Another type, with time-delay characteristics, has a different construction. It has a compound element composed of a spring and a link. On moderate overloads, when the tem-

Table 2-4—Specifications for Three Types of Aircraft Fuses (Limiters)*

Type	Rating: amp	Rating: volts, ac	Interrupting capacity (amp)	Remarks
A (See Fig. 2-7)	1-100	120	4000 at 120 volts, 400 cycles, 50,000 ft alt. Arc time less than 1/2 cycle	These units have arc-suppressing lining
B	5-60	120	———	These units—with arc-suppressing lining (5-30 amp) or sand filled (40-60 amp) —were developed to improve arc interruption under high surge voltages
C	1-60	120	4000 at 115 volts ac; 5000 at 120 volts ac	

* From Barlow, S. P. "Electrical Distribution Systems for Modern U. S. Aircraft," Engineering Report No. 6584, The Glenn L. Martin Co., Baltimore, Md. (Also ASTIA AD No. 53124).

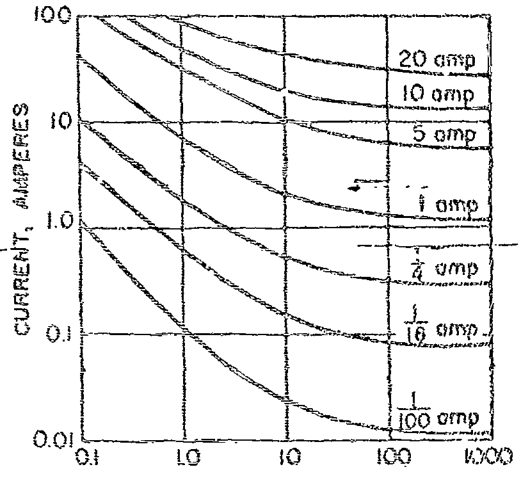


Fig. 2-5. Current-time-to-blow characteristics of time-delay fuses.

perature of the compound element reaches the melting point of the alloy, the spring pulls away from the link. On short circuits the link blows. The construction of these two types of fuses is shown in Fig. 2-8 and their current-time-to-blow characteristics are shown in Figs. 2-9 and 2-10.

Indicating Fuses. The fuses discussed thus far all had glass cylinders enclosing the fusible element. When the fuse is blown, the molten element is clearly visible. Other fuses, having the same physical sizes and electrical ratings as the glass-enclosed, are made with opaque tubes. When this type of fuse is blown, there is no visible evidence of it; and an electrical test is necessary to detect a blown fuse in equipment. Some of these opaque fuses, therefore, have an indicating pin that extends from the end of the fuse when the fuse is blown. Other methods of indicating

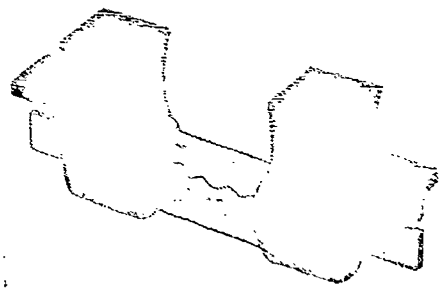


Fig. 2-6. Aircraft fuse (limiter). (Burndy Engineering Co., Inc.)

blown fuses, when the fuse element is not visible, are discussed under Fuse Mounts.

Fuse Mounts

Fuses are generally connected into circuits by fuse holders which make it easy to replace a blown fuse by a new one. Two main types of fuse holders for cartridge fuses are the extractor post-type holders and fuse blocks.

Extractor Post-Type Holders. This type of holder is mounted on the front of a panel and is widely used to hold 1- by 1/4-inch, 1-1/4- by 1/4-inch, and 1-1/2- by 13/32-inch fuses. It has a coiled spring that creates positive contact pressure on the ends of a fuse when the cap is in place. The cap is either bayonet type or screw type and tightly grips the fuse, pulling it from the holder when the cap is removed. Screw caps may be either knurled or fluted and are removed by finger pressure.

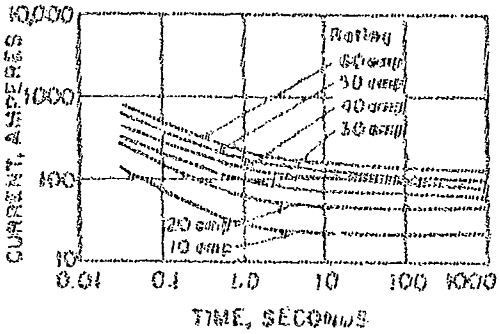


Fig. 2-7. Current-time-to-blow characteristics of aircraft fuse (limiter), Type h, Table 2-4.

Many post holders have been made of phenolics, but because of their low arc resistance the trend has been towards higher arc-resistant materials such as melamine, Teflon, and glass-bonded mica. Post holders may be either opaque or transparent. The opaque type does not give any indication of a blown fuse; therefore, when the circuit does not operate, a test is required to determine whether the fuse is blown. The transparent types have a built-in indicating lamp, either neon or incandescent, that can be seen through the cap, and lights up when the fuse is blown. Other types have a transparent cap through which the indicating pin on the end of a blown fuse is visible.

Holders that require a screwdriver for removal of the blown fuse are not generally recommended for Air Force equipment.

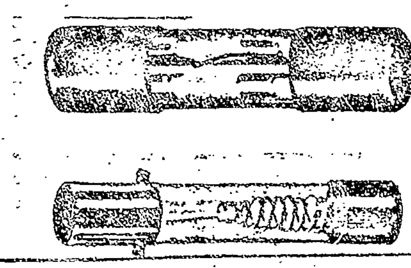


Fig. 2-8. Construction of vibration-resistant fuses. (A) Normal lag. (B) Time delay. (Littelfuse Inc.)

Fuse Blocks. These holders are made of an insulating base on which are mounted fuse clips. They are made in single, double, and three-pole forms; and if desired, can be made in the form of panel boards having as many fuse clips as required. Some fuse blocks have insulating barriers between the clips to prevent flashover from one circuit to another.

Fuse Clips. Fuse clips are generally made of spring bronze or beryllium copper. Both of these materials have high electrical conductivity and good spring-like properties that are necessary to make a firm contact between the fuse terminals and the fuse holder. They are made with or without end stops. Some representative types of fuse holders are shown in Fig. 2-11.

Military Fuse and Fuse-holder Specifications

Fuses, and the fuse holders associated with them, in common with other components used for military purposes, have a series of specifications that cover their uses and requirements. Some of these specifications have a basic section that specifies materials of

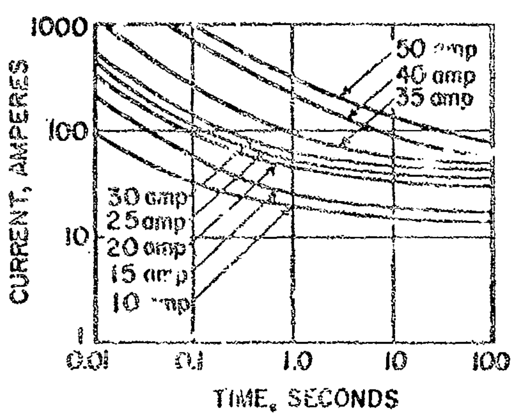


Fig. 2-9. Current-time-to-blow characteristics of vibration-resistant normal-lag fuses.

which the fuses are made and the test methods and requirements that fuses must meet. Appended to these specifications are detailed specification sheets that show dimensions and details of the fuses covered by these specifications. On the other hand, there are other specifications that are limited to only one type and size of fuse. Summaries of the major fuse specifications follow.

MIL-F-15160C, Fuses; Instrument, Power, and Telephone. This is the basic military fuse specification. It is a general specification, giving some construction details, specifying the grades of materials to be used and test requirements. Specific construction details of each type of fuse are given in Military Standard Sheets that are appended to the specification. Fuses made according to this specification have to meet requirements for electrical continuity, current carrying capacity, overload blowing, terminal strength, and short circuit tests.

In this specification, fuses are designated in the following form:

F01	G	R010	B
Style	Voltage rating	Current rating	Characteristic

Style is designated by the letter "F" followed by a two-digit number denoting a fuse of given construction and dimensions.

Voltage rating is the maximum nominal d-c or a-c rms voltage for which the fuse is designed. It is identified by one letter in accordance with Table 2-5.

Current rating is the nominal amount of current a fuse will carry indefinitely without blowing. It is identified by a combination of a three-digit number and the letter "R", which indicates the decimal point, as shown in Table 2-6.

The characteristic is identified by one letter which indicates relative blowing time as shown in Table 2-7.

MIL-F-1887, Fuse, Time-Delay, 0.150 Ampere. This specification covers only one type of time-delay fuse consisting of a tubular laminated phenol fiber body with nickel-plated brass ferrules and enclosing a time-delay element. The fuse is 1-1/4 inches long by 3/8 inch in diameter. The diameter over the ferrules is 0.400 to 0.410 inch. The resistance of the element is not to exceed 50 ohms. The

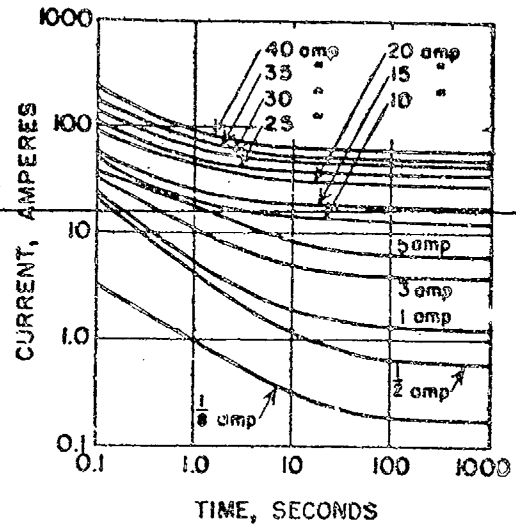


Fig. 2-10. Current-time-to-blow characteristics of vibration-resistant time-delay fuses.

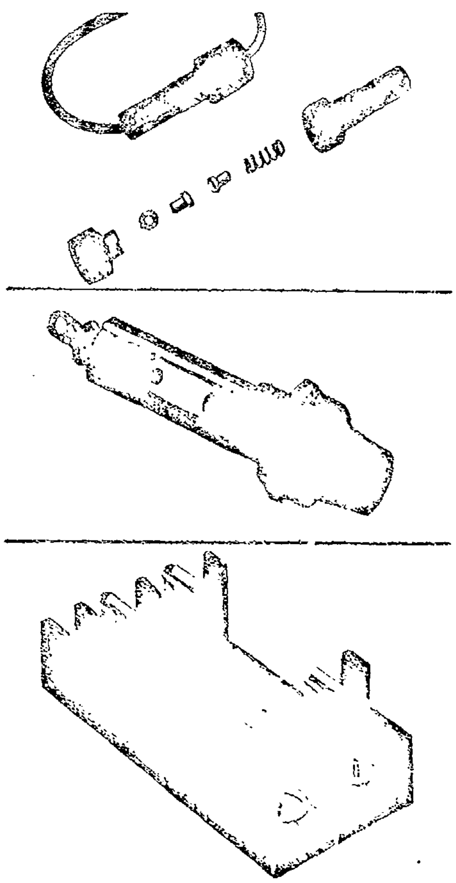


Fig. 2-11. Representative types of fuse holders. (A) Post holders for cartridge fuses. (B) Holders for aircraft fuses (limiters).

Table 2-5—Voltage Rating of Fuses Made in Accordance with MIL-F-15160C of 15 April 1953

Symbol	Voltage (max)
A	32
B	62
C	90
D	125
G	250
H	500
J	1,000
L	2,500
N	5,000
P	10,000

fuse is to carry 0.150 amp indefinitely, and to interrupt 3 amp at 600 volts dc. Its delay characteristic is 0.5 second to 2 seconds for 0.25-amp and 15 to 40 seconds for 1-amp loading. The fuse has to meet mechanical strength tests and is to be "so constructed as to give reasonable assurance of withstanding deterioration in storage for a period of ten (Par E-9 of specification)

MIL-F-5372B, Fuse Enclosed Link, Aircraft. This specification covers single-element fuses rated from 5 to 100 amp and used in 115/200 volt, 400 cycle circuits. The fuses are self-indicating and do not require removal from the fuse blocks for checking. Current-time-to-blow and ambient-temperature correction curves are included in the specification. The interrupting capacity of the fuses is 4000 amp at 120 volts rms (400-cycle) and 3500 amp at 208 volts rms (400-cycle) with the arcing time limited to 1/2 cycle. Each fuse has to carry its rated load for 1000 hours and retain its operating characteristics without maintenance. It shall also be capable of operating under the following conditions:

1. Minimum ambient temperature of -65 C.

Table 2-6—Current Rating of Fuses Made in Accordance with MIL-F-15160C of 15 April 1953

Symbol	Current rating (amp)
R001 to R009	0.001 to 0.009
R010 to R099	0.010 to 0.099
R100 to R999	0.100 to 0.999
1R00 to 9R99	1.00 to 9.99
10R0 to 99R9	10.0 to 99.9
100R to 999R	100. to 999.

Table 2-7—Characteristics of Fuses Made in Accordance with MIL-F-15160C of 15 April 1955

Symbol	Relative blowing time
A	Normal (normal interrupting capacity)
B	Time lag
C	Normal (very high interrupting capacity)

2. Maximum ambient temperature varying uniformly from 85 C at sea level to 2 C at 23,000 feet and remaining constant thereafter until 50,000 feet.

3. An altitude range from sea level to 50,000 feet.

4. Exposure to fungi encountered in tropical and semitropical climates.

5. Exposure to salt-laden atmosphere.

6. Relative humidity from 0.5 to 100 percent.

7. Exposure to airborne sand particles encountered on deserts.

8. Conditions of linear vibration incident to normal continuous use in aircraft.

9. Operative in an explosive vapor within or surrounding equipment.

These fuses are to be used with the fuse holders described in MIL-F-5373B.

MIL-F-19207(Ships), Fuseholders, Extractor Post Type, Blown Fuse Indicating and Nonindicating. This specification covers fuse holders designed for use with instrument and power fuses covered by MIL-F-15160. These fuse holders may be of the nonindicating or the blown fuse indicating types, and they have provisions for panel mounting.

Fuse holders made in accordance with this specification are identified in the following manner:

FH L10 G

Style Characteristics Enclosure

where

Style is composed of two letters, FH, indicating fuse holder

Characteristics is composed of a letter (either L, blown fuse indicating type; or N, nonindicating type) and a two-digit number indicating the design, construction, and physical dimensions of a particular fuse holder

Enclosure is represented by a single letter (either G, sealed to give some degree of watertightness; or U, unsealed).

These fuse holders cannot be made of flammable or explosive material or material that can produce toxic or suffocating fumes when the fuse holders are in service, nor can their current carrying parts be made of any material containing more than 5-percent iron. If molded plastic material is used in fabricating these fuse holders, it must conform to MIL-P-14. Any metals used in these fuse holders must be either corrosion resistant or treated to resist corrosion. The use of dissimilar metals in contact is not permitted unless they are protected against electrolysis.

When resistors are used in indicating-type fuse holders, they must be in accordance with MIL-R-11 and have values that are specified for each fuse holder. Indicating-type fuse holders must also have knobs that are made of transparent high-temperature polystyrene in accordance with MIL-P-3413.

Fuse holders made in accordance with this specification have to meet specified requirements for dielectric strength, insulation resistance, contact resistance, current overload, endurance, temperature rise, short circuit current, vibration, shock, acceleration, and moisture resistance, and they must be explosion proof.

Other Specifications

There are other specifications for fuses with nonmilitary characteristics or requirements. They are:

W-F-791a	Fuses; Cartridge, Inclosed, Nonrenewable
W-F-803a	Fuses; Cartridge, Inclosed, Renewable (Fusible Links Not Separately Inclosed), and Renewable Links Therefor
W-F-805	Fuses; Cartridge, Inclosed, Renewable (Fusible Link Separately Inclosed)
W-F-831	Fuses; Plug, Nonrenewable
Jan-F-1131	Fuse-Indicators, Lamp-Type

CIRCUIT BREAKERS

A circuit breaker, like a fuse, can be used to protect either circuits or equipment. In additi n, a circuit breaker can also be used as a switch. As a protective device, a circuit breaker should be able to carry rated current indefinitely and to trip with a definite time-delay characteristic when an overload occurs. As a switching device, it should be able to make and break rated current without excessive arcing at the contacts.

There are two basic types of circuit breakers—the magnetic type, which depends upon the electromagnetic effect of a current in a coil; and the thermal type, which depends upon the heating effect of current in a bimetallic element. The details of each type are given in the sections that follow.

Magnetic Circuit Breakers

The tripping mechanism of a magnetic circuit breaker is actuated by a solenoid that has a movable iron core within a hermetically sealed tube extending through and below the coil. The tube is completely filled with a viscous liquid that controls the rate at which the core will be attracted by the solenoid. This controls the time-delay characteristic of the circuit breaker on overloads.

When an overload occurs, the movable core, which is held away from the poleface by a compression spring, is attracted by the solenoid at a rate that is a function of the ampere-turns of the coil, the viscosity of the fluid, and the size of the orifice or the passage around the core. As the core moves further into the magnetic field of the solenoid, the flux increases until it is strong enough to attract the armature sufficiently to trip the breaker. Thus, any desired time-delay characteristic can be readily built into a circuit breaker.

The action of a circuit breaker tripping on a short circuit is different from its action on overloads. When a short circuit occurs, the current through the coil is of such a high magnitude that the magnetomotive force produced overcomes the reluctance of the airgap, attracts the armature, and tripping is instantaneous.* The working parts of a circuit breaker are shown in Fig. 2-12.

*"Instantaneous" is a qualifying term indicating that no delay is purposely introduced in the action of the circuit breaker. There is necessarily a time delay (about 0.01 second) between the occurrence of a short circuit and the tripping of the circuit breaker because of the inertia of the tripping mechanism.

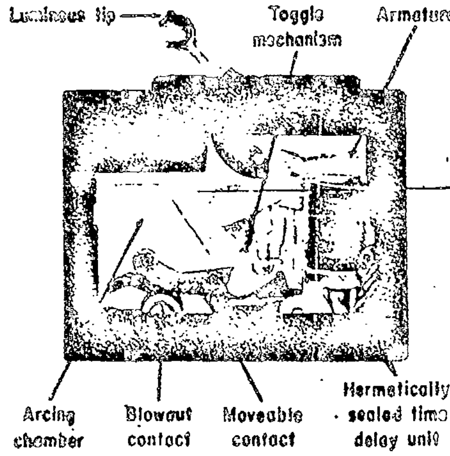


Fig. 2-12. Working parts of a magnetic circuit breaker. (Heinemann Electric Co.)

Circuit breakers can be used in several ways in electronic circuits. The conventional method is the series overload trip. Other methods commonly used are the shunt trip, relay trip, and the calibrating tap. The distinguishing features of each type are discussed in the following sections.

Series Overload Trip. This method of circuit breaker application is the best known and most widely used to protect electronic circuits and equipment. The trip coil and contacts are in series with the load across the supply voltage. This arrangement is used when the circuit breaker acts as the main switch and overload protective device in electronic equipment, or is used for overload and short circuit protection of components. The circuit arrangement is shown in Fig. 2-13.

Shunt Trip. In this application the trip coil is in parallel with the load, and the contacts are in series with both the load and the trip coil, as shown in Fig. 2-14. Circuit breakers

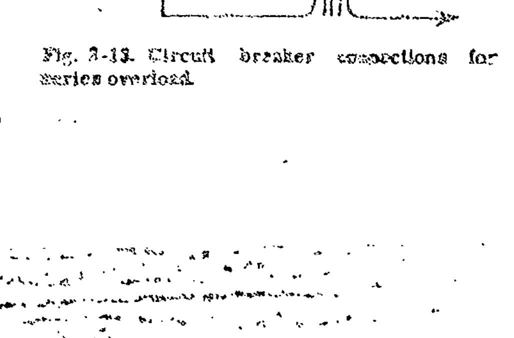


Fig. 2-13. Circuit breaker connections for series overload.

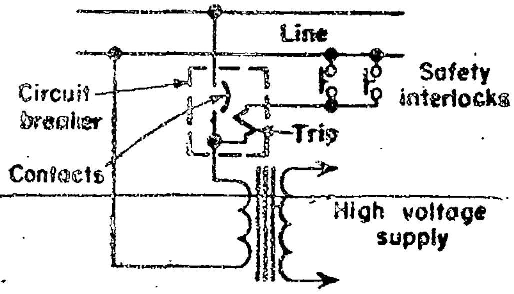


Fig. 2-14. Circuit breaker connections for shunt trip.

of this type have three terminals per pole—line, load, and shunt-trip terminals. One end of the trip coil is connected internally to one of the load terminals and the other end to the shunt-trip terminal. By using this type of circuit breaker, remote switching is possible through circuit closing contacts located in a control or safety interlock. These interlocks can be sensitive to, and their operation dependent upon, temperature, pressure, humidity, time, or any other parameter that can be measured.

Relay Trip. This type differs from the series and shunt-trip types by having the trip coil and the contacting element electrically isolated from each other. This type of circuit breaker has four terminals per pole, since the trip coil and the switching mechanism each need two terminals. Its basic design is shown in Fig. 2-15. Since the coil circuit is

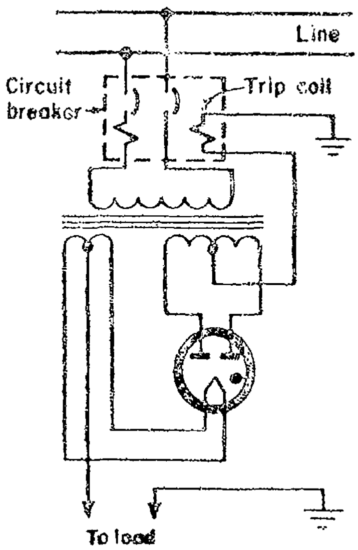


Fig. 2-15. Circuit breaker connections for relay trip.

independent of the contact circuit, it may be operated at a different voltage from the line voltage. When the equipment to be protected is operating at high voltage or high current, the trip coil of the circuit breaker may, therefore, be operated at a low voltage or low current and still give all the protection required by the equipment.

Calibrating Tap. This construction is similar to the series overload trip, except that an additional terminal at the common point of the contact and the trip coil is provided, as shown in Fig. 2-16. This type of circuit breaker allows the trip coil to be shunted by a fixed or variable resistor to bypass some of the load current. Changing the value of the shunting resistor allows the load current to be raised, without increasing the size of the circuit breaker.

Reverse Current Trip. This type of circuit breaker is used on d-c circuits. It has two

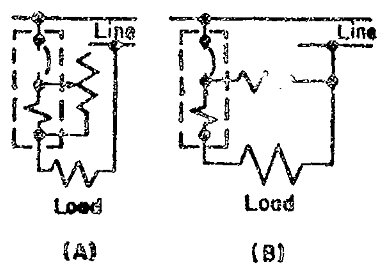


Fig. 2-16. Circuit breaker connections for calibrating tap construction. (A) Variable shunting resistor. (B) Fixed shunting resistor.

windings on one coil form—a series winding and a shunt winding—connected in such a manner that the fields produced by the coils are in opposition to each other when the current flows in the forward direction. When the current flow increases beyond overload in the normal or forward direction, the field produced by the series coil increases until it is strong enough to overcome the opposing flux set up by the shunt coil and trip the breaker. When the current is reversed in the series winding, the fields produced by the series and shunt coils are additive and produce a flux strong enough to trip the breaker when a preset value of reverse current is attained.

Characteristics. The prime requisite of any circuit breaker is its tripping characteristic. Other requirements, such as operating temperature, humidity and pressure ranges, resistance to vibration and shock, and fungus resistance may be necessary for the proper

functioning of a circuit breaker; but they are all subsidiary to the main requirement of the tripping characteristic.

From the standpoint of tripping characteristic, there are two types of circuit breakers: (1) instantaneous circuit breakers, which are used where there is no current inrush or surge; their principal use is to protect meters and instruments and (2) time-delay circuit breakers, which are used to protect equipment because a certain amount of inrush and surge current is permissible if the duration of the current is not excessive.

Time-Delay Characteristics. Representative time-delay characteristics are shown in Fig. 2-17. Comparison of these curves will show that as the frequency increases, the duration for any given load decreases. This is a desirable condition since the heating effect of a given current increases with its frequency. In this figure, curve 1 allows the longest time delay and is used where a circuit is protecting an individual motor: curve 2 is an intermediate characteristic used in circuits where there are several pieces of equipment; and curve 3 allows a high inrush current for a relatively short time and is used in the protection of electronic equipment and components.

The curves in Fig. 2-17 show the trip characteristics of circuit breakers at 25 C ambient temperature. When the temperature varies from this value, correction curves are required to show how the time delay is affected by the ambient temperature. Different liquids used in the time-delay tube give vastly different ambient temperature characteristics. Representative curves for two liquids are shown in Fig. 2-18.

Although ambient temperature affects the time delay of a magnetic circuit breaker, it

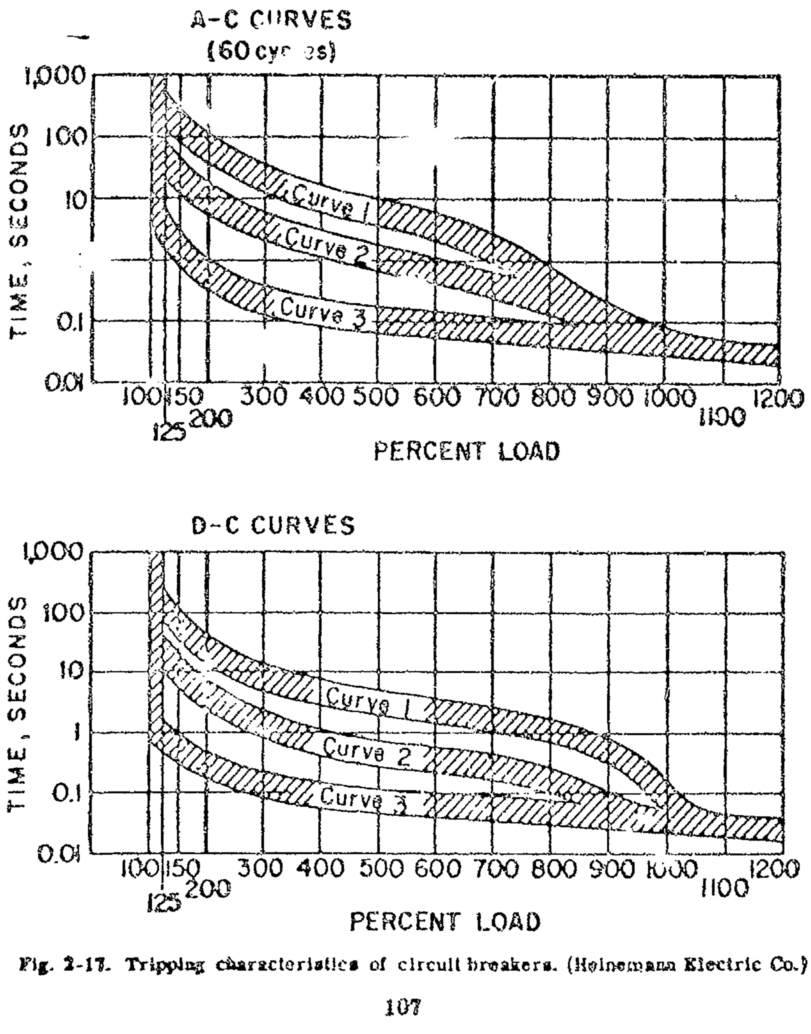


Fig. 2-17. Tripping characteristics of circuit breakers. (Heinemann Electric Co.)

functioning of a circuit breaker; but they are all subsidiary to the main requirement of the tripping characteristic.

From the standpoint of tripping characteristic, there are two types of circuit breakers: (1) instantaneous circuit breakers, which are used where there is no current inrush or surge; their principal use is to protect meters and instruments and (2) time-delay circuit breakers, which are used to protect equipment because a certain amount of inrush and surge current is permissible if the duration of the current is not excessive.

Time-Delay Characteristics. Representative time-delay characteristics are shown in Fig. 2-17. Comparison of these curves will show that as the frequency increases, the duration for any given load decreases. This is a desirable condition since the heating effect of a given current increases with its frequency. In this figure, curve 1 allows the longest time delay and is used where a circuit is protecting an individual motor; curve 2 is an intermediate characteristic used in circuits where there are several pieces of equipment; and curve 3 allows a high inrush current for a relatively short time and is used in the protection of electronic equipment and components.

The curves in Fig. 2-17 show the trip characteristics of circuit breakers at 25 C ambient temperature. When the temperature varies from this value, correction curves are required to show how the time delay is affected by the ambient temperature. Different liquids used in the time-delay tube give vastly different ambient temperature characteristics. Representative curves for two liquids are shown in Fig. 2-18.

Although ambient temperature affects the time delay of a magnetic circuit breaker, it

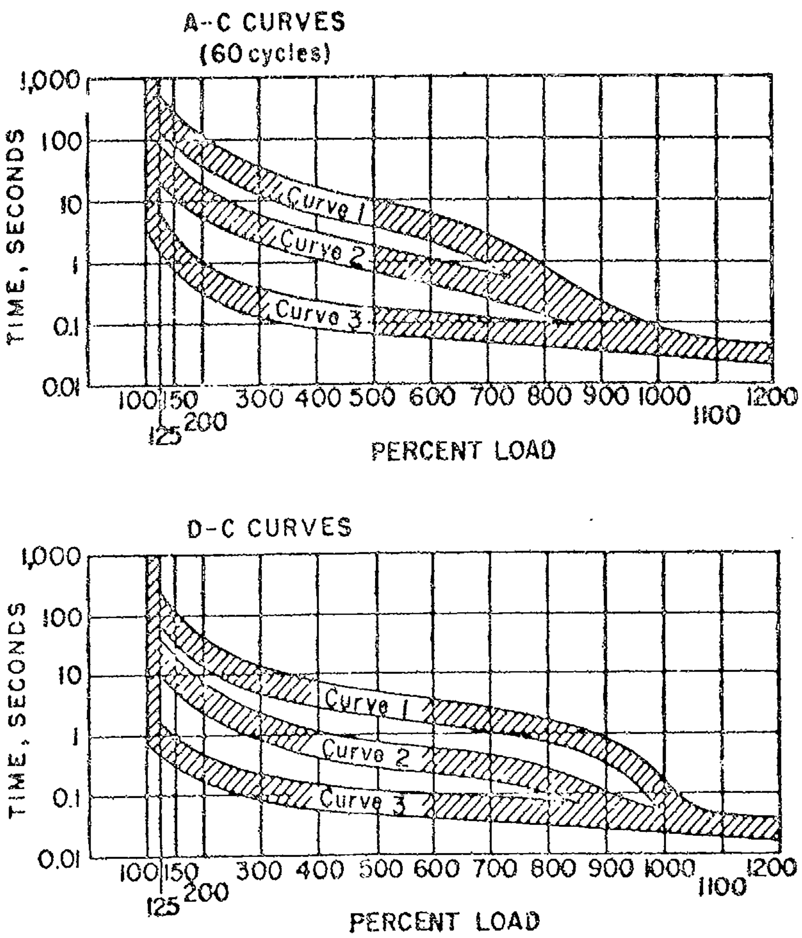


Fig. 2-17. Tripping characteristics of circuit breakers. (Heinemann Electric Co.)

does not influence the current-carrying capacity or the instantaneous-trip point of the breaker. These points are determined by the magnetomotive force produced by the current through the trip coil, and this function is practically independent of temperature.

The ambient temperature effects, illustrated in Fig. 2-18, are desirable since at low temperatures equipment can carry an overload for a greater time, and at high ambient temperatures for a shorter time, than at normal (25 C) temperature.

Thermal Circuit Breakers

The tripping action of thermal circuit breakers depends on the heating effect of an electric current in a bimetallic element. When rated current or less flows through the bimetal strip, the circuit breaker remains in the closed position. On overloads the bimetallic element is bent by the heating effect of the current until a latch releases the movable contact or contacts and opens the circuit.

Time-Delay Characteristics. Thermal circuit breakers, like magnetic circuit breakers, have an inverse time-delay characteristic. A large current will cause the circuit breaker to trip in a shorter time than a small current. Since thermal circuit breakers require a finite time for the bimetallic element to heat up, regardless of the current, they do not have an instantaneous trip time as defined

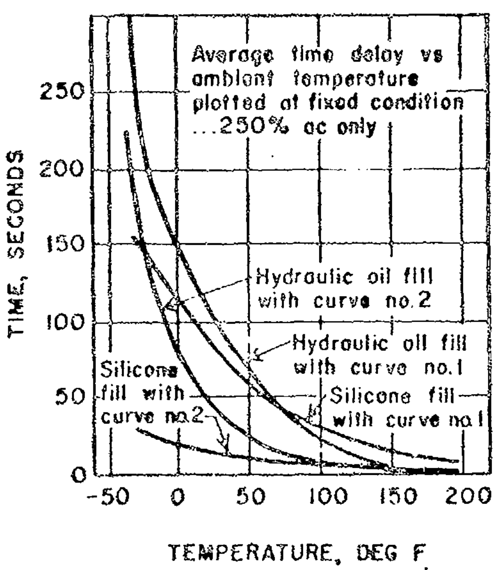


Fig. 2-18. Average time delay of a magnetic circuit breaker at 250 percent of a-c load as a function of ambient temperature (See Fig. 2-17).

under magnetic circuit breakers. Their time-delay characteristics are shown in Fig. 2-19.

Specifications

Circuit breakers, like other components used in military electronic equipment, have coordinated and noncoordinated specifications. The major circuit breaker specifications used by the three servic. , arranged in numerical order are summarized in the following paragraphs.

MIL-C-5809B(ASG), Circuit Breakers, Trip-Free, Aircraft. This specification covers push-pull type and switch type, single-pole, trip-free circuit breakers from 5 to 125 amp for use in a-c and d-c aircraft electrical systems, and has been approved by the Air Force and the Navy Bureau of Aeronautics.

It specifies components and materials to be used in the fabrication of circuit breakers, and has a precautionary note against the use of dissimilar metals in contact; or, where their use is unavoidable, a provision for protection against electrolytic corrosion. This specification also has a chart showing how the trip current varies with ambient temperature.

Appended to this specification are five military standard sheets that give outline drawings, dimensions, ratings, close-in and rupture currents, open-circuit recovery voltage, and the maximum weight of each circuit breaker.

MIL-C-7079, Circuit Breakers, Nontrip-Free. This specification consists of an old specification AN-C-77a, dated 20 April 1944; amendment 3, dated 22 December 1948, and a cover sheet with the statement, "For reference purposes, Specification AN-C-77a is considered cancelled and superseded by Specification MIL-C-7079; however, copies should be retained for attachment to this cover sheet until this military specification is revised, at which time Specification AN-C-77a should be discarded." It covers single-pole, nontrip-free aircraft circuit breakers rated from 5 to 50 amp at 30 volts dc. The general provisions concerned with materials, components, and dimensions parallel those in MIL-C-5809B(ASG) for equally rated circuit breakers. The tests generally follow those specified in MIL-C-5809B(ASG) with the exception of humidity resistance, fungus resistance, and explosionproof requirements. Circuit breakers made in accordance with MIL-C-7079 are constructed to prevent flames

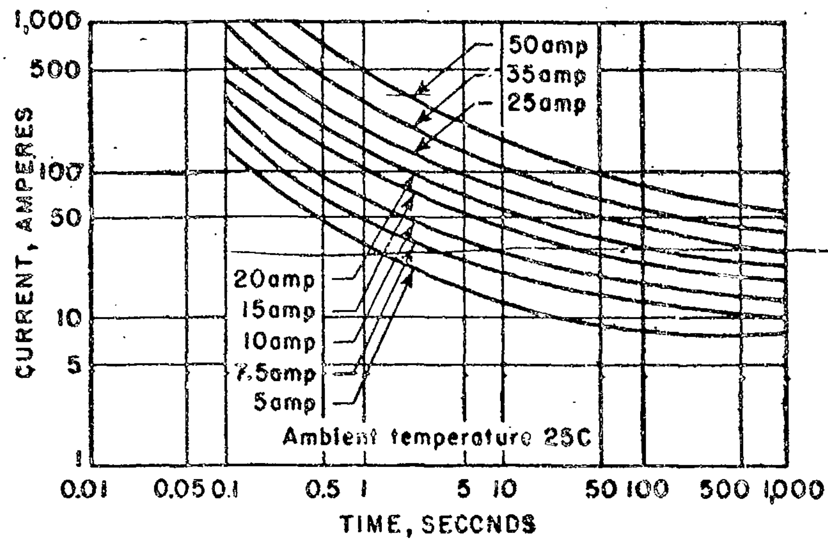


Fig. 2-19. Thermal circuit breaker time-delay characteristics.

from escaping during make and break operations at rated current and any altitude up to 50,000 feet. Their contacts are not to fuse when the breakers are held closed for 10 seconds at 400 percent of rated current or for 90 seconds at 250 percent of rated current.

Nonelectronic Circuit Breaker Specifications

The following circuit breaker specifications are given for reference only, since they cover circuit breakers for power and lighting circuits.

MIL-C-8379A(ASG), Circuit Breaker, Electrically Operated, 3-Pole, Type A-1. This specification covers a solenoid-operated 3-pole air circuit breaker for operation in the main line circuit of 40-kva, 30-kw, 208/120-volt, 400-cycle, 3-phase, grounded neutral, engine-driven alternators in large aircraft.

MIL-C-12433(CE), Circuit Breaker, Special Purpose, Manually Operated, Surface Mounted, Sheet Steel Enclosed. This specification covers special purpose manually operated circuit breakers for use in protection of lighting and light duty power circuits.

MIL-C-14144(CE), Circuit Breakers, Manually Operated, Surface Mounted, Sheet Steel Enclosed, 3-Pole. This specification covers manually-operated circuit breakers for outdoor applications in protection of lighting and power circuits in the field.

MIL-C-17361(Ships), MIL-C-17587(Ships), and MIL-C-17588A(Ships). These specifications cover circuit breakers as applied to navy vessels.

APPLICATION NOTES

1. In selecting a fuse or a circuit breaker, the equipment designer should answer the following questions:

a. What is to be protected?

b. What voltage is to be interrupted by the protector?

c. What is the normal current through the component to be protected?

d. What is the maximum abnormal current through the component?

e. How long can the component carry this abnormal current without damage?

f. Will the circuit protector be subjected to any vibration or shock?

2. All leads from the primary service lines should be protected by fuses.

3. Fusing of circuits should be such that rupture or removal of a fuse will not cause malfunction or damage to other elements in the circuit.

4. Fuses should be connected to the load side of the main power switch. Holders for branch-line fuses should be such that when correctly wired, fuses can be changed without the hazard of accidental shock. At least one of the fuse-holder connections should be normally inaccessible to bodily contact, and this

terminal should be connected to the supply; the accessible terminal should be connected to the load.

5. Provisions for storage of spare fuses should be made at an accessible location.

6. If simple element fuses are used to protect vibrators or choppers, they may be subjected to cyclic fatigue brought about by the expansion and contraction of the element because of the intermittent current flow. Time-delay fuses, which usually have elements capable of withstanding expansion and contraction, are better under these circumstances.

7. Instrument fuses should be coordinated with the instruments that they protect.

8. The basic rule in fuse application is: use the highest fuse rating consistent with adequate protection. Fuses, like any other device, are prone to aging. They should be operated below their rated current whenever possible.

9. A very common error in circuit protection is the use of a protector with current-time-to-blow characteristics that do not correspond with the characteristics of the equipment or component to be protected. The outstanding example of this is the use of normal-lag fuses to protect motors, especially when the motor takes a high starting current. Time-delay fuses, which can carry both the starting current and running current of the motor, are the proper devices to be used in this instance.

10. Under short-circuit conditions, a thermal or time-delay protector with a relatively low current rating may require more time to open than a fast-acting type with a considerably higher rating.

11. Fuses with a rating of 1-amp and less are fragile and susceptible to rupture by vibration or shock. The reliability of the fuse has to be considered with the probability of circuit malfunction and the necessity for protection.

12. Fuses may blow because of overheating brought about by poor contacts rather than because of any fault in the circuit or equipment.

13. Circuit breakers can be reset in less time and with less trouble than is required to replace blown fuses, and spare parts are seldom required. They may, therefore, be preferable where continuity of service is an important consideration or where frequent fuse replacement may be expected. The first cost of circuit breaker equipment is somewhat more than the cost of fuse equipment; but under severe service, circuit breakers will be less expensive over the life of the equipment.

14. In the protection of circuits, a great deal of confusion exists on the necessity of speed to interruption of the circuit. Since the circuit protector can be considered from two viewpoints—(1) protection against short circuits and (2) protection against overloads—the conditions of protection are almost diametrically opposite for these conditions. To protect against short circuits, speed is wanted—the more speed the better. In protection against overloads, some allowance has to be made for harmless temporary overloads that often occur in the warmup periods when equipment is first turned on. In this instance the circuit protection device should not operate unless the overload persists.

Variations in ambient temperature may change the characteristics of thermal circuit breakers to the point where adequate protection is not given to equipment, or else the circuit breaker may operate needlessly. At low temperatures the circuit breaker may not give adequate protection, if the characteristics of the bimetallic strip are not coordinated with the equipment that the circuit breaker is to protect; while at higher temperature the bimetallic strip may be so heated that it causes unnecessary circuit interruptions.

Contents

CHAPTER 3 ELECTRICAL INDICATING INSTRUMENTS

Chapter 3

ELECTRICAL INDICATING INSTRUMENTS

The function of an electrical measuring instrument is to translate the magnitude of an intangible flow of electric current to the tangible position of a pointer along a calibrated scale. The pointer deflection of all electrical measuring instruments is a function of the current through the actuating coil of the instrument.

For current measurements, the actuating coil is connected in series with the circuits to be measured; full scale deflection in most instruments usually requires 1 to 10 ma through the coil. When currents larger than those that can be accommodated by the coil are to be measured, a low-resistance shunt is placed internally in the instrument case and connected across the coil. The magnitude of the coil current then becomes a finite fraction of the indicated current, and the face markings of the instrument are scaled proportionately to this fraction. The instrument usually has so little resistance (compared to the measured circuit) that there is no appreciable interference with the normal operation of the measured circuit.

Voltage measurements are made with a current measuring instrument by means of a resistance in series with the actuating coil, and the entire assembly is placed in parallel with the potential to be measured. With the scale marked in terms of voltage, the series resistance is adjusted so that when full-scale voltage is applied, full-scale current will flow through the coil. The series resistance is characteristically high enough so that the instrument will not appreciably interfere with the normal operation of the circuit being measured.

Further, the instrument current may be supplied from a transducer such as a thermocouple, so that the instrument will read current in terms of temperature, and the scale is calibrated in degrees; or the instrument may be connected to a tachometer generator giving a voltage proportional to speed. The scale is then marked in rpm. Thermocouples, tachometers, and other transducers are discussed further in later sections.

Definitions

As the discussion progresses, the matter of definitions becomes important. Each of the military and industrial specifications listed in a later section includes a number of definitions. The definitions of the same items are not always identical in all of these specifications; however, they do not differ materially from the basic instrument standard, the American Standard for Electrical Indicating Instruments, C39.1-1955, of the American Standards Association. Any difference in wording is for clarification rather than a deviation from the basic definitions.

A few of the more important definitions are given below. They were taken directly (or paraphrased) from ASA Standard C39.1 referenced above. Other definitions will be found where they apply to the particular discussion.

Indicating Instrument. An instrument in which only the present value of the quantity measured is visually indicated.

Self-Contained Instrument. An instrument which has all the necessary equipment built

into the case, or made a corporate part thereof.

Mechanism. The arrangement of parts for producing and controlling the motion of the indicating means. It includes all the essential parts necessary to produce these results, but does not include the base, cover, dial, or any parts, such as series resistors or shunts, whose function is to adapt the instrument to the quantity to be measured.

Moving Element. Those parts which move as a direct result of a variation in the electrical quantity which the instrument is measuring. The weight of the moving element includes one-half the weight of the springs.

Note: The use of the term "movement" is discouraged.

Influence. The change in the indication of the instrument caused solely by a departure of a specified variable from its reference value, all other variables being held constant.

External-Temperature Influence. The percentage change (of full-scale value) in the indication of an instrument which is caused solely by a difference in ambient temperature from the reference temperature.

Where military specifications indicate a requirement for the maximum effect of heat upon the instrument, it is stated that the meter shall indicate fr at 65 C and the difference between the ing at this temperature and at 25 C shall, in general, be not greater than from 2 to 20 percent (depending upon the meter type) and the permanent change shall not be greater than from 2 to 4 percent after a series of temperature cycling tests, the great variations being allowed the small instruments.

Accuracy Rating. The limit, usually expressed as a percentage of full-scale value, which errors will not exceed when the instrument is used under reference conditions.

In general, military specifications require the initial accuracy of an instrument to be of the order of 2 to 3 percent, with the greater figure applying to the 1- and 1-1/2-inch instruments.*

* The accuracy rating is intended to represent the tolerance applicable to an instrument in an "as received condition." Additional tolerances for the various influences are permitted when applicable. Generally the accuracy of electrical indicating instruments is stated in terms of the electrical quantities to which the instrument responds. In instruments with the zero at a point other than one end of the scale, the arithmetic sum of the end-scale readings to the right and to the left of the zero point shall be used as the full-scale value.

Military specifications, in general, set limits to the permanent changes allowed for errors in indication after stated amounts of vibration and shock and temperature excursions have been applied. Military Specification M-10304A is of particular importance in that it covers ruggedized meters that are required to show less than stated amounts of error after being subjected to high values of shock, vibration, temperature excursions, and immersion in water. Maximum allowable values of friction are also stated. Where high values of vibration and shock and exposure to the elements may be expected, as is usually the case in military applications, the ruggedized instruments in accord with this specification should be used.

Speed of Indication

When electrical energy is applied to an electrical measuring instrument, or when the energy value changes, the pointer should respond promptly and indicate the existing value without delay. It should not oscillate unduly before coming to rest. Further, if the voltage or current applied is, in itself, changing rapidly, the instrument pointer should follow those changes. On the other hand, if the voltage changes very rapidly, as in the output of a speech amplifier, or of a code transmitter, it may be preferable to have a response which is delayed a bit and which tends to average out very rapid fluctuations. Thus, the overall instrument dynamics must be considered in some detail.

To adequately discuss instrument response to the applied electrical energy, a few definitions from C39.1 are set forth here:

Damping. The term applied to denote the manner in which the pointer settles to its steady indication after a change in the value of the measured quantity. Two general classes of damped motion are distinguished as follows: (1) periodic, in which the pointer oscillates about the final position before coming to rest, and (2) aperiodic, in which the pointer comes to rest without overshooting the rest position. The point of change between periodic and aperiodic damping is called critical damping.

Note: An instrument is considered to be critically damped when overshoot is present, but does not exceed an amount equal to one-half the rated accuracy of the instrument when determined in accordance with the note under "Damping Factor" below.

Overshoot. The ratio of the overtravel of the indicator beyond a new steady deflection to the change in steady deflection when a new constant value of the measured quantity is suddenly applied. The overtravel and deflection are determined in angular measure and the overshoot is usually expressed as a percentage.

Note: Since, in some instruments, the ratio depends on the magnitude of the deflection, a value corresponding to an initial deflection from zero to full scale is used in determining the overshoot for rating purposes.

Damping Factor. The ratio of the deviations of the pointer in (the first) two consecutive swings (in the same direction) from the position of equilibrium, the greater (first) deviation being divided by the lesser (second). The deviations are expressed in angular measure. Where military specifications set limits to the damping factor, the value varies from 1.5 to 3.5 maximum depending upon the type of instrument.

Note: Since, in some instruments, the damping factor depends upon the magnitude of the deflection, it is measured as the ratio in angular degrees of the steady deflection to the difference between maximum angular momentary deflection and steady angular deflection produced by a sudden application of a constant electric power. The damping factor specified shall be determined with sufficient constant electric power applied to carry the pointer to full-scale deflection on the first swing. The damping shall be due to the instrument and its normal accessories only.

For practical purposes, the damping factor is simply the reciprocal of the overshoot. That is, if, say, 10 volts is suddenly and initially applied to a 15-volt instrument, and the needle kicks up to 11 volts on its first deflection, this is an overshoot of 1/10 of the final deflection, or 10 percent; and the damping factor is 10. If the steady voltage already on the instrument had been 5 volts, and then 5 volts more had been applied so that the new steady deflection again becomes 10 volts, the overshoot (assuming the needle again kicks up to 11 volts) would have been 1/5, or 20 percent, and the damping factor would have been 5. On d-c instruments having a uniform scale, the overshoot may be taken between any two points; however, if the scale is nonlinear it is best if overshoot measurements are taken from scale zero.

Response Time. The time required after an abrupt change has occurred in the measured quantity to a new constant value until the pointer, or indicating means, has first come to apparent rest in its new position.

Military specifications which set maximum limits to the response time, in general, require the value to be not over 2 to 3 seconds depending upon the type of instrument involved. Since, in some instruments, the response time depends on the magnitude of the deflection, a value corresponding to an initial deflection from zero to end scale is used in determining the response time for [illegible] purposes. The pointer is at apparent rest when it remains within a range on either side of its final position equal to one-half the accuracy rating.

Response time involves both damping and speed of action. The instrument designer considers response time in terms of the natural undamped period of the moving system and the degree of damping.

In a practical sense, a short response time makes rapid indication possible and is generally desirable. It is best obtained in an instrument by having an overshoot of less than 20 percent; d-c mechanisms can generally be designed with an optimum of 5 to 10 percent overshoot. Other types of mechanisms are less readily damped and a damping factor of 1.5 minimum, equal to an overshoot of 67 percent is usually allowed on iron vane a-c instruments. This is permitted because damping in these instruments must be obtained by auxiliary means, such as a damping vane in an air chamber or in a separate shielded magnetic system.

Very high speeds are usually obtainable only on special order. They are costly to build and take more power than standard types. Since the eye can barely follow the motion of a normal instrument pointer, very high-speed instruments are seldom used as indicating instruments.

Low-speed heavily damped instruments are valuable where rapidly fluctuating voltages or currents must be indicated. They are more costly than standard types and are needed only occasionally. The VU meter used in broadcasting monitoring is only moderately slow; its response time is 0.3 seconds with an overshoot of 1 to 1.5 percent.

The speed of an instrument may be specified by calling for a given response time, usually with an appropriate tolerance of 10 percent, and a damping factor or percent overshoot. These two items will completely

govern the dynamics of all linear scale instruments. Although nonlinear scale instruments do not follow the above exactly, they are usually also specified in this manner.

TYPES OF MECHANISMS

Measuring instruments are frequently grouped according to the different kinds of operating mechanisms they contain.

Permanent Magnet Movable Coil (PMMC) Instruments

This type, which responds basically only to direct current, is the most common type of mechanism. Because of its high sensitivity, much less than 1 mw being required for full-scale deflection, the mechanism may be used with relatively inefficient converting devices to measure alternating current and potential as well as to indicate resistance values. Damping is usually excellent, torque is good, and the mechanism is relatively immune to moderate shock and vibration. Because of its requirement for little energy, only very large electrical overloads will burn it out. In fact, such auxiliary items as series resistors, shunts, and thermal converters, are more subject to electrical damage than the instrument mechanism itself.

The PMMC mechanism consists of a permanent magnetic system producing a heavy flux density (from 1500 to 3000 gauss) in the air-gap in which the actuating coil moves. The coil is pivoted, usually at its center. Thus, the gap is circular and the magnetic field is radial within it. With an external magnet, the structure of Fig. 3-1 results; in some instances the internal or core magnet system of Fig. 3-2 is used. With either type, the

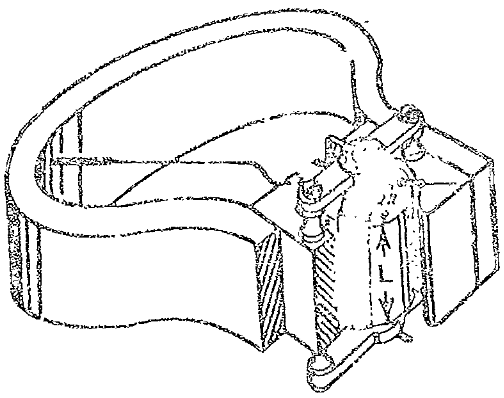


Fig. 3-1. Conventional magnetic system for a d-c instrument.

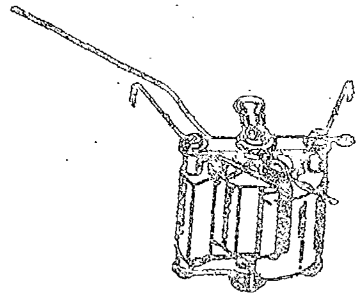


Fig. 3-2. Magnetic system for a d-c instrument with a core magnet.

radial airgap is small, 0.05 to 0.08 inch. To maintain constant flux in this airgap, the structure must be sufficiently rigid to avoid changes in the gap length due to vibration, shock, or temperature change, and the magnet itself must have a sufficiently long body to ensure that the magnet is truly permanent.

The moving coil is usually wound on an aluminum frame which serves as a coil support and also furnishes damping due to eddy currents generated in it when moving in the magnetic field. The coil winding may vary from 10 to 1000 turns, and have a resistance of from a fraction of 1 ohm to as much as 1000 ohms. Pivot bases cemented to the coil carry the pivots, pointer, balance cross and springs. The pivots rotate in V-jewel bearings, spring-supported in many instances, as shown in Fig. 3-3.

In the conventional 90-degree scale form, actually 80 to 110 degrees, such a mechanism in a 2- or 3-inch case can be designed for any d-c measurement. It will withstand, without damage, instantaneous overloads of 100 times the top scale value or ten times the top scale value indefinitely, provided, however, that there be no more than 500 volts across the terminals and not over 2 watts dissipated in the instrument for over a few seconds. With a few milliwatts dissipation, the normal rated accuracy is 2 percent of full scale in most instances, with adequate speed and optimum damping.

Long-Scale Instruments. Where the pointer must move 200 to 250 degrees, a more involved magnetic system with a moving coil pivoted off center, as shown in Fig. 3-4, is required. Long-scale instruments are basically less accurate than those with the 90-degree scale because, in the latter, the arrangement of the concentric bore and the core tend to balance out mechanical imper-

fections. Further, the flux density in the long-scale instruments is limited because of the structure itself and the total flux must be spread over a greater gap. On the other hand, long-scale instruments are more readable. They usually require more power to operate and are more difficult to damp. They are inevitably more expensive than instruments with the 90-degree scale. In general, these long-scale instruments are suitable only for special applications where the deficiencies mentioned can be accepted in the application and where readability is of prime importance, with sensitivity and accuracy lesser requirements.

This type of instrument is more susceptible to shock and vibration and, in the panel type, is lacking in ruggedness. In some special instances, as in the large switchboard type developed primarily for Naval use, adequate resistance to shock and vibration has been secured.

It is worth noting that 90-degree scales are used for all laboratory grade instruments with rated accuracies of better than 1 percent.

Ranges and Applications. Instruments with PMMC mechanisms with internal shunts for currents up to about 30 amp, and connected to external shunts for higher currents (MIL-S-61A), are used to measure direct current. The more sensitive types, milliammeters, are used for plate current measurements. Microammeters, available as low as 20 microamperes full scale, are used as indicators in nuclear radiation instruments and monitors. A voltmeter for direct current consists of a sensitive milliammeter, usually 1 ma full scale, with internal resistance, 1000 ohms per volt full scale, for up to 300 volts. Higher ranges, used as plate voltmeters in radio transmitters, for example, require external resistors per JAN-R-29. Millivoltmeters operating from a thermocouple are used as temperature indicators. An example is an electrical thermometer for exhaust gases. Special compensation in the form of a negative temperature coefficient carbon resistor may be included in the instrument.

Because of the large number of ranges that might be selected for military use, many of the specifications give preferred ranges, which should always be used. More specifically, Military Specification M-10304 lists the ranges to be used for new equipment. These ranges are shown in Table 3-1.

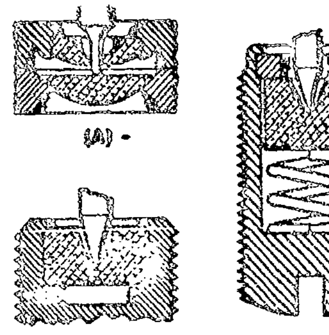


Fig. 3-3. Plain and spring-cushioned V-jewel instrument bearings: (A) Ring and end stone jewel bearing, (B) V-jewel bearing, and (C) Spring-back jewel bearing.

Millivoltmeters. It should be noted that a millivoltmeter is not merely a milliammeter used as such, but rather is a milliammeter with added series resistance to bring it to a specific value of both full-scale millivolts as well as resistance. When a millivoltmeter is placed across a shunt, it is activated by a drop in that shunt in terms of millivolts. Similarly, if used for monitoring currents in several circuits by being placed in shunt to an accurately adjusted resistance in those circuits, the millivoltmeter again must be adjusted to a specific resistance. The practice of placing a milliammeter of standard current range across a resistance for monitoring purposes should be avoided because milliammeters, as such, are never adjusted to a specified resistance, and, further, even though the resistance is known and taken into consideration, no temperature compensation of

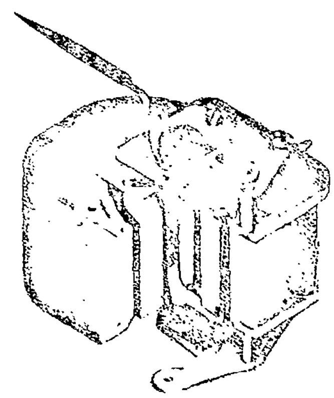


Fig. 3-4. Magnetic system for long-scale instruments.

Table 5-1—Preferred Ranges—Ruggedized Meters
Applies to 2-1/2- and 3-1/2-Inch Sizes
Except as Indicated

<table>
<tr><th colspan="6">A-C Meters</th></tr>
<tr><th colspan="2">Ammeters</th><th colspan="2">Milliammeters</th><th colspan="2">Voltmeters</th></tr>
<tr><td colspan="2">0-1, 0-2, 0-5, 0-10, 0-20, 0-50, 0-100(1), 0.200(1), 0-500(1)</td><td colspan="2">0-10, 0-30, 0-50, 0-100, 0-200, 0-500</td><td colspan="2">0-1.5(3), 0-3, 0-5(2), 0-8, 0-10(2), 0-15, 0-30, 0-80, 0-150, 0-300(4)</td></tr>
<tr><th colspan="6">D-C Meters</th></tr>
<tr><th colspan="2">Ammeters</th><th colspan="2">Milliammeters</th><th colspan="2">Voltmeters</th></tr>
<tr><td colspan="2">0-1, 0-2, 0-5, 0-10, 0-20(5), 0-50(5), 0-100(5), 0-200(5), 5-0-5, 10-0-10, 10-0-30(5), 20-0-30(5), 30-0-30(5)</td><td colspan="2">0-1, 0-5, 0-10, 0-50, 0-100, 0-300, 0-500, 1-0-1, 5-0-5, 10-0-10, 50-0-50, 100-0-100, 500-0-500</td><td colspan="2">0-2, 0-10, 0-20, 0-50, 0-100, 0-200, 0-300(6)</td></tr>
<tr><th colspan="2">Kiloammeters</th><th colspan="2">Microammeters</th><th colspan="2">Kilovoltmeters</th></tr>
<tr><td colspan="2">0-1(5), 0-1.2(5)</td><td colspan="2">0-20, 0-50, 0-100, 0-200, 0-500, 50-0-50, 100-0-100, 500-0-500</td><td colspan="2">0-1(6), 0-3(6), 0-5(6), 0-10(6), 0-20(6), 0-30(6)</td></tr>
<tr><th colspan="6">R-F Meters</th></tr>
<tr><th colspan="3">Ammeters</th><th colspan="3">Milliammeters</th></tr>
<tr><td colspan="3">0-1, 0-2, 0-5, 0-10, 0-20</td><td colspan="3">0-100, 0-200, 0-500</td></tr>
</table>

Notes: (1) Used with external current transformer
(2) Preferred only for 2-1/2-inch meters
(3) Preferred only for 3-1/2-inch meters
(4) Supplied with external resistor
(5) Used with external shunt
(6) Used with external resistor

this resistance has been arranged as is the case in a millivoltmeter. Milliammeters and microammeters, with adjusted resistance for use as millivoltmeters, are listed in many of the specifications and should always be used where the requirement is essential for a millivoltmeter to be shunted across an appropriately adjusted resistance in a circuit or circuits.

To consider the matter of temperature compensation of millivoltmeters in greater detail, it is generally necessary to add several times as much zero temperature coefficient resistance wire, in ohms, as in the meter moving coil, to limit a millivoltmeter error due to temperature to 1 percent for a change of 10 C. Where wide temperature excursions are to be expected, more complicated procedures are required, such as the use of a more elaborate network or the addition of carbon resistors, which have a negative temperature coefficient, to cancel the positive coefficient of the copper moving coil. Normally, millivoltmeters are considered as compensated if the change in indication as a millivoltmeter is less than half the rated accuracy for a temperature change of 10 C. But this may add up to several percent if operated at temperature extremes. There appears to be no simple answer to this problem and where high accuracy is required at temperature extremes, an engineering study of the instrument circuit as a whole is usually required.

Ohmmeters and Capacitance Meters. A very common application of the d-c mechanism is as an ohmmeter. Resistance is added to the mechanism as in a voltmeter, and a dry cell or a dry cell battery or another source of d-c voltage is placed in series with it along with a pair of terminals for connection to the external resistance being measured. The internal resistance is such as to allow for full-scale deflection on the battery volt-

age available. If the external resistance across the resistance terminals is zero, the meter then indicates full scale; if it is equal to the internal total circuit resistance, then the indication is half scale. To mark off other scale points, the following equation can be used:

$$\text{Percent deflection in terms of full scale current} = \frac{\text{Internal resistance} \times 100}{\text{Internal resistance} + \text{External resistance}}$$

However, battery voltage varies and since the scale in ohms is a function of the internal resistance, it is a good practice to establish the internal resistance at some even value and adjust for the existing battery voltage by a variable resistance shunt around the mechanism only, as shown in Fig. 3-5. Adjustment of this shunt makes little change in the total resistance; the adjustment is made to full-scale deflection with the external resistance terminals shorted. Selection of values of internal resistance, battery voltage, mechanism current for full scale, and shunt adjusting resistance will all depend upon the resistance range requirements. In general, for testing with a single dry cell, the lower the full-scale current value the higher the internal resistance and the higher the deflection for a given external resistance.

For still higher resistance ranges, additional battery and internal resistance is needed. Lower value scales are arranged by shunting the mechanism and internal series resistance for a lower effective total resistance. See Fig. 3-6 for a typical diagram of a 5-range ohmmeter.

Similarly, an a-c voltmeter may be used as a capacitance meter. Assuming the voltmeter circuit to be purely resistive, as is usually the case, and when operated on an adjusted alternating voltage of fixed frequency giving full scale when the external terminals are shorted, the scale can be pointed off by the following equation:

$$\text{Percent deflection in terms of full scale current} = \frac{\text{Internal resistance} \times 100}{\text{Total circuit impedance}}$$

where the total circuit impedance is equal to the square root of the sum of the squares of the capacitive reactance in ohms (at the frequency used) and the internal resistance. If a rectifier-type voltmeter is used, adjustment for available voltage and fixed internal resistance may be made by shunting the moving coil itself.

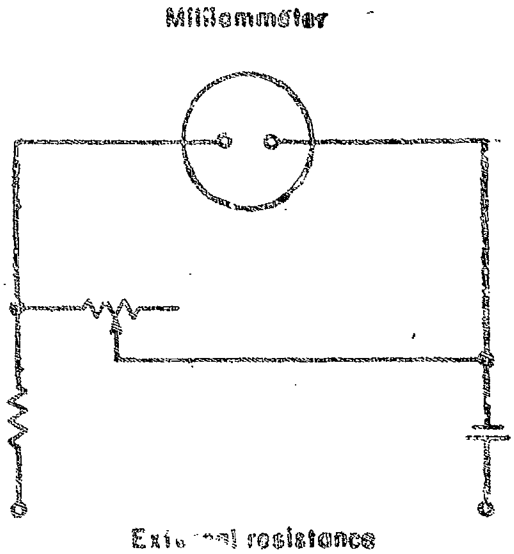


Fig. 3-5. Schematic diagram of milliammeter used as series ohmmeter with meter shunt adjustment for battery voltage variation.

Since indicating instruments are for use in all positions, it is very necessary that the moving element itself be in exact balance. That is, the moving element, when swung between its bearings and with no spring torque, should assume any position; unbalance would cause it to take a specific position by the force of gravity when the axis was horizontal. Effectively, this means that when under the control of the springs, the zero position of the pointer should not change when the instrument is horizontal, vertical, or on its side. All moving systems are supplied with a balance cross of some sort, which carries, in turn, balance weights that are adjustable in their distance from the axis and which are adjusted in assembly to obtain the required true balance. The balance cross and sliding weights can be seen in Figs. 3-1, 3-3, 3-4, 3-7(A), and 3-7(B).

Balance can be checked by setting the instrument to zero with its face horizontal. When brought into a vertical position, any material movement of the pointer is due to unbalance. This lack of perfect balance is called position influence in some standards and is usually limited to the same value as the allowable error for a 90-degree tilt in panel and switchboard instruments. In portable instruments, operated with the face horizontal, balance is specified in terms of allowable tilt for a stated error. However, portable instruments operated horizontally generally show very small effects of this kind.

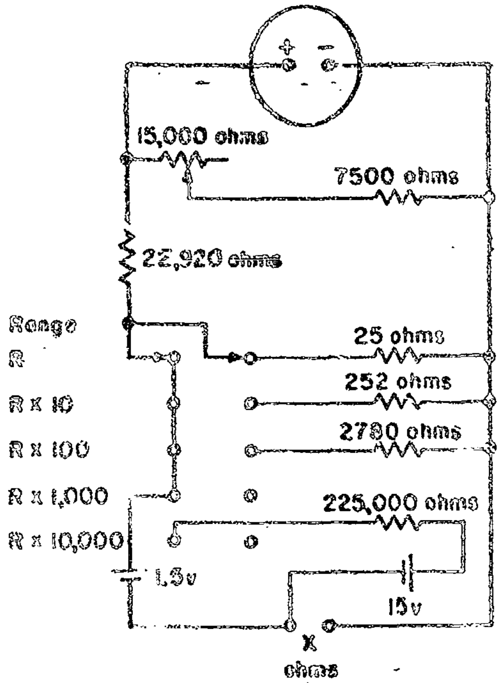
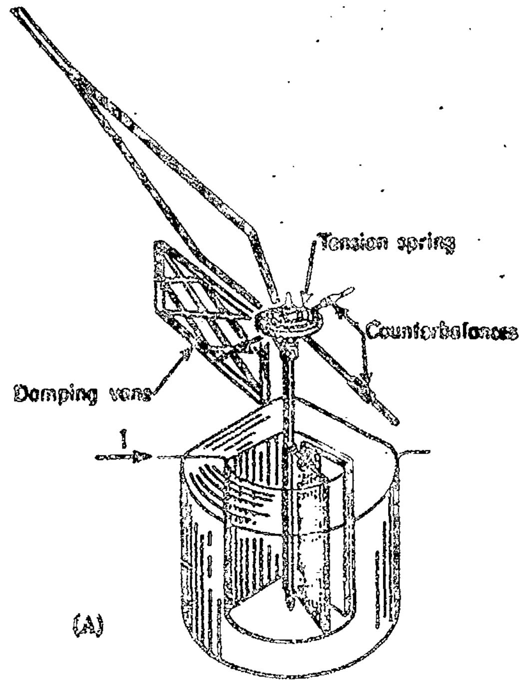


Fig. 3-6. Multirange ohmmeter, scale 0-300 ohms, 20 ohms at center, using 5-position double-pole switch for range selection.

A-C Instruments

For a-c power, the simple repulsion iron vane mechanism of Fig. 3-7 is very satisfactory. Requiring about 60 ampere-turns for full-scale deflection, the mechanism is simple and sturdy. As shown in Fig. 3-7(A), the moving and fixed vanes are magnetic cores within the activating coil; when the coil is energized, both are magnetized with the same polarity and will repel in proportion to the current through the coil. Note that the energy required in the coil is several hundred milliwatts, over a thousand times as much as in the PMMC type. Damping is obtained by auxiliary means; for example, by an aluminum vane in an air chamber or in the field of a shielded permanent magnet assembly.

Because the iron vanes saturate magnetically at high-flux densities, instantaneous overloads rarely cause damage unless they are due to high voltage breaking down the coil insulation. Prolonged overloading should be limited to only a few times full-scale value, with 2 to 3 watts being a top limit for sustained loads.



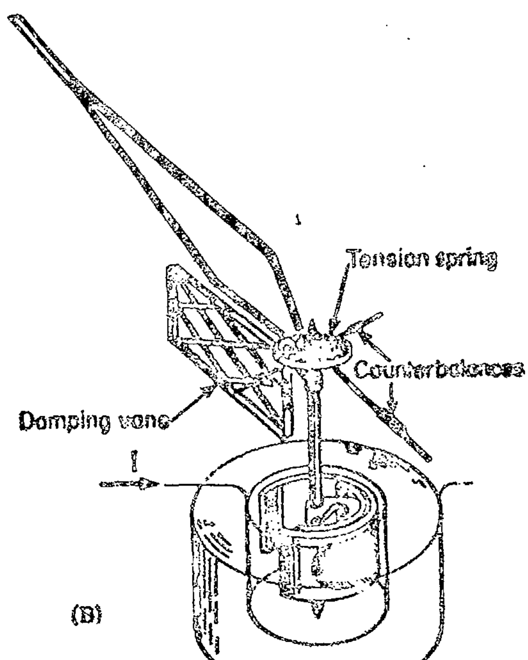


Fig. 3-7. Two types of iron vane mechanisms: (A) Radial vane mechanism—both most-linear and sensitive scale and (B) Concentric vane mechanism—moderately sensitive, square law-scale characteristics.

In the panel sizes used in aircraft, iron vane instruments are generally available only in the nominal 90-degree scale types. They are used for indicating the voltage and current existing in a-c power systems either in aircraft or in ground equipment.

Iron vane ammeters and milliammeters are subject to a small frequency error at the higher power frequencies due to eddy currents being generated in the iron vanes themselves which will produce an additional magnetic reaction to that produced by the flux of the main coil. This effect upon accuracy is small, however, and roughly of the order of 1 percent at 1000 cycles. Note that the inductive drop across an ammeter will become large at the higher frequencies. For example, a 5-amp ammeter of the portable type, having a coil inductance of approximately 0.02 mh, has an impedance of 1.25 ohms at 10,000 cycles. The drop at 5 amp is then 6.25 volts, requiring 31 volt-amp for full-scale deflection. Panel instruments may require half this amount of power. Thus, the iron vane ammeter requires a large amount of reactive power at the higher power frequencies and may materially affect the circuit in which it is placed so that for frequencies much over 2500 cycles the thermoammeter is preferred.

An iron vane voltmeter, basically a milliammeter in series with appropriate impedance, is subject not only to the frequency error due to eddy currents in the iron vanes but also to the fact that the impedance rises with frequency so that at the higher frequencies less current passes through the actuating coil. With pure resistance in series with a normal coil, the top frequency for good accuracy is limited to perhaps 150 cycles although this varies with different makes and different designs; this applies to switchboard, panel, and portable instruments. The series impedance can be adjusted at the frequency in question so that the instrument will read correctly at a specific calibrated frequency but with an error at other frequencies.

Frequency compensation for the rising impedance characteristic of an a-c voltmeter can be arranged as shown in Fig. 3-8(A). (1) In essence the network is arranged so that as the reactance of the field coil increases with frequency, the reactance of the series resistance shunted by the capacitance is reduced in a similar fashion to maintain more uniform current in the actuating coil as the frequency rises. In general, this arrangement will allow for a ten-fold expansion of the frequency span which can be covered by an iron vane instrument not so compensated. Figure 3-8(B) shows the results of compensating a conventional iron vane voltmeter. (1) In general, the top compensated frequency is about 2500 cycles for iron vane and electrodynamometer instruments of all types.

Where a voltmeter is ordered for a specific frequency, it is standard procedure to supply an instrument which will be within its guarantee over a frequency range of from 10 percent below to 10 percent above the frequency specified and the instrument may or may not include a compensation network depending on its basic design. Iron vane instruments designed and adjusted for use on 60, 400, and 800 are listed in the several military specifications; instruments adjusted for other frequencies up to 1200 cycles are readily available.

Instruments required to measure correctly at several different frequencies can usually be obtained on special order. Because they require a rather complex frequency compensation network, they are generally more expensive than instruments adjusted for a single frequency. Portable instruments of higher accuracy for ground use or laboratory testing are generally available covering broad frequency spans.

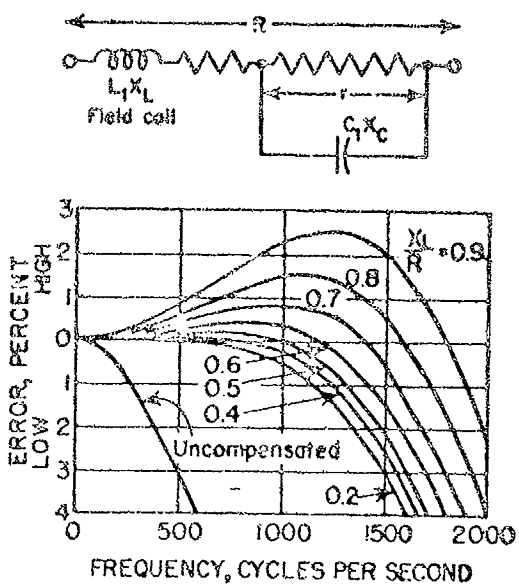


Fig. 3-8. Frequency compensation in a-c instruments: (A) Compensating circuit, (B) Errors in 5000-ohm voltmeter having 0.4-h inductance and compensated at various frequencies; the curves are marked with the parameter X_L/R for the compensated frequency.

Instruments of the moving magnet type for d-c use are mentioned here but are rarely used in aircraft. Typified by the charging indicators on automobiles, they are of limited accuracy, require considerable energy for operation, and are justified only as inexpensive indicators.

Electrodynamometer. This type of mechanism consists of a moving coil rotating in the magnetic field produced by a set of fixed coils. Figure 3-9 shows the general structure. The operating torque tending to rotate the pointer against the control springs is proportional to the product of the currents in the moving and fixed coils. The most important use of the electrodynamometer mechanism is as a wattmeter where the main current flows through the fixed coils directly and a small current proportional to and derived from the voltage flows through the moving coil. (See Fig. 3-0). The pointer thus indicates the in-phase product of the two, or watts.

When the field coils are wound of fine wire and connected in series with the moving coil and appropriate series resistance, an electrodynamometer voltmeter results. It automatically indicates true rms values. Such instruments in the laboratory type of 1/4 percent of full-scale accuracy, are necessary for precision calibration and test. Electrodynamometer voltmeters and wattmeters may be frequency-compensated in a manner similar to iron vane voltmeters. Ammeters are similarly made but usually with a portion of the current shunted around the moving coil.

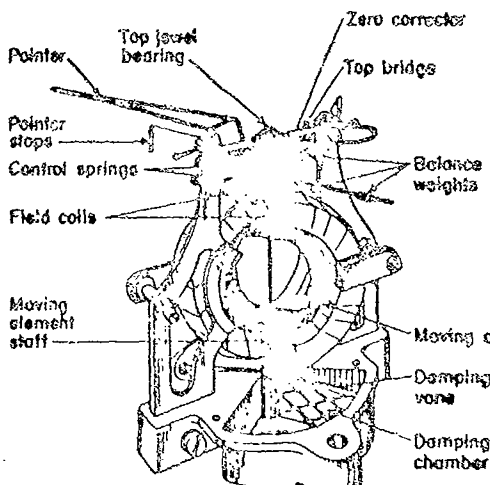


Fig. 3-9. Electrodynamometer mechanism showing heavy fixed coil, fine wire moving coil, and air-damping vanes.

Instruments as described rarely are used as panel instruments in aircraft. A modified version, containing iron lamina to strengthen the field is sometimes used for power measurements in aircraft a-c power systems; the adding of iron to the field structure reduces the basic accuracy, however, and the structure tends to be rather on the complicated side. Generally, the electrodynamometer type of mechanism is limited to use in the laboratory and occasionally for ground and field testing.

Thermoammeters. These instruments are employed in the measurement of high-frequency currents, generally above 100 kc. They consist essentially of a d-c instrument and a thermoelement. The thermoelement is shown in Fig. 3-10(A) and schematically in Fig. 3-10(B). The high-frequency current passing through the heater between the terminal studs A and B raises the temperature of the center point E. The temperature rise of point E over that of the terminals is practically a pure function of the square of the current. A thermocouple of two dissimilar metals, platinum and nickel for example, is welded to the center point of the heater and, because of the temperature difference between the center point of the heater and the ends of the couple, a (thermoelectric) voltage is generated which is proportional to this temperature difference. This voltage is applied directly to a PMMC mechanism with a full-scale sensitivity of about 12 mv and the scale is then marked in terms of the main current through the heater. Although the conversion efficiency of this combination is very poor, perhaps 1/10 of 1 percent, the power sensitivity of the d-c mechanism is so high that a very satisfactory high-frequency ammeter is possible, taking about 1 watt for a 5-amp full-scale instrument.

Because of the high temperature at which the heater operates, it must be made of a noble metal, such as platinum or one of its alloys. Because the temperature rises as the square of the current, overloads are dangerous and a 100 percent overload is likely to damage the instrument. In spite of this limitation, the thermoammeter is the only type of direct reading instrument suitable for r-f currents and is used widely for measuring antenna current in radio equipment of all types. However, even with a tubular heater, as offered by some makers, the skin effect of high frequency currents comes into play and at 100 Mc such an instrument may be in error by 5 percent. Therefore, thermoammeters are not used much above 60 Mc. The time

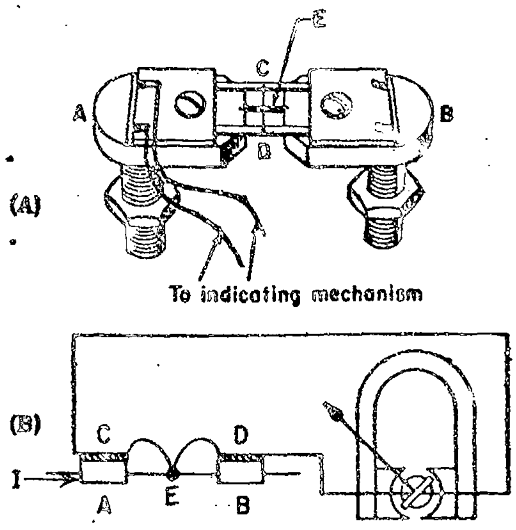


Fig. 3-10. Thermoelement as used in a r-f ammeter: (A) Physical arrangement and (B) Schematic diagram.

constant of the thermal converters in these instruments is about 0.2 second and they will be damaged by heavy short pulses lasting longer than a few milliseconds.

Thermal Wattmeter. Figure 3-11 shows a schematic arrangement whereby two thermoelements with insulated thermocouples can be used to give an ouput in millivolts proportional to true power. With more complicated circuitry, thermal power converters are available for both single and polyphase systems which are used occasionally to give a power indication on a relatively simple d-c power instrument.

If, at a given instant, the current from the secondary of the current transformer is that of the plain arrows, and the direction of the current in the potential circuit is that of the flagged arrows, then the heating effect at A is a function of the sum of these two currents, and the heating effect at B is the difference. Since the heating effect is proportional to the square of the currents involved, and since the outputs at A and B are connected in opposition, the total potential developed across the instrument will be the difference of the squared currents at these two poin

Rectifier-Type Instruments. These instruments utilize copper oxide dry-disk rectifiers so that a typical PMMC mechanism can be calibrated to read alternating current. The rectifier can be very small so that at 1 ma, for example, it is operating at good efficiency, perhaps 90 percent of the optimum. Although germanium and silicon diodes are more perfect current rectifiers than the copper oxide type, their inherent resistance is higher. Thus, for best efficiency, as in the VU meter and other voice-frequency monitoring units, copper oxide remains the preferred type. Figure 3-12 shows a typical copper oxide rectifier unit as used in measuring instruments.

Because of the requirement for very small sizes in the rectifier disk to maintain reasonably high-current density, rectifiers for use in instruments are usually considered a specialty item and are particularly processed for this use. Conventional rectifiers of larger sizes will usually show very low efficiency when operated at very low levels. Permanence of contact is also a problem, and one maker gold-sputters both surfaces of small disks to give a nonoxidizing contact.

Figure 3-13 shows typical d-c characteristics of small disks as processed for instrument rectifiers; the largest disk being rated at 5 ma maximum, the 0.13-inch disk being rated at 2 ma, and the smallest disk at 1 ma. Such disks will stand twice the rating but will usually be either broken down or materially degraded at four times their rated currents.

Waveform Errors. When an alternating voltage or current is to be measured, the effective or root-mean-square (rms) value is usually wanted. This is the value needed for all power calculations and is normally implied in a statement of a given value of alternating voltage or current. But if 100 volts ac of good sine-wave form, for example,

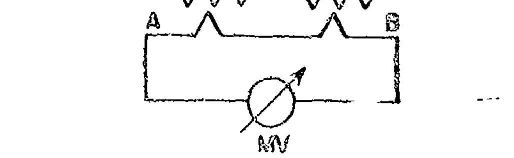


Fig. 3-11. Schematic diagram of a thermal wattmeter.

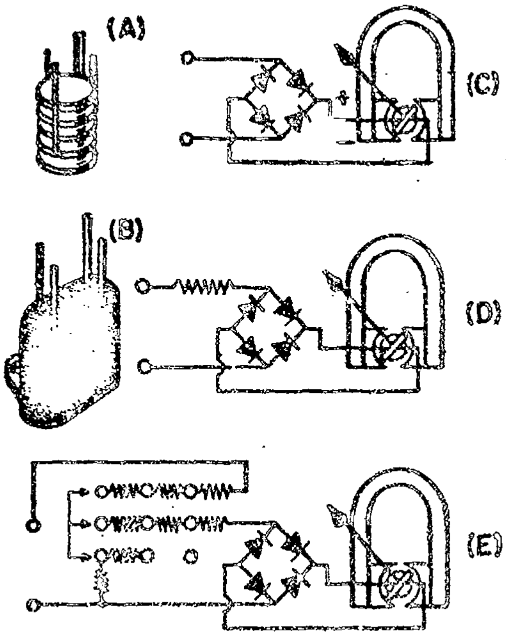


Fig. 3-12. Typical copper oxide bridge rectifier as used in rectifier instruments: (A) Assembly of disks, (B) Disks sealed in bakelite housing, (C) Milliammeter, (D) Voltmeter, and (E) DB and VU circuits.

is rectified and applied to a 100-volt d-c meter, the average value of 90 volts will be read even though the *rms* value is still 100 volts. Actual practice is to adjust the calibration of any rectifier-type instrument so that the indication on the scale is the *rms* value of an applied alternating current or voltage of pure sine-wave form. If direct current is applied to a *rectifier meter* so

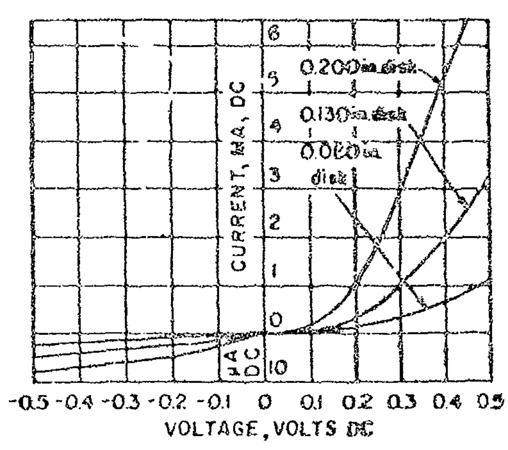


Fig. 3-13. D-C characteristics of instrument-type copper oxide rectifiers.

calibrated, the reading will be about 11 percent high.

Another approach to the same end result is to consider the ratio of direct current and rms alternating current in the output and input to a bridge rectifier, and the curves of Fig. 3-14 indicate the approach to a maximum ratio of 0.9 at the rated current levels. Note also that a somewhat lower ratio applies at lower currents. This simply means that a rectifier-type instrument will have its scale cramped at the lower portion because there is not a fixed proportionality between the input and output. Therefore, the most efficient rectifier for the current rating of the instrument in question should be selected so that the least amount of change in ratio exists over the scale range.

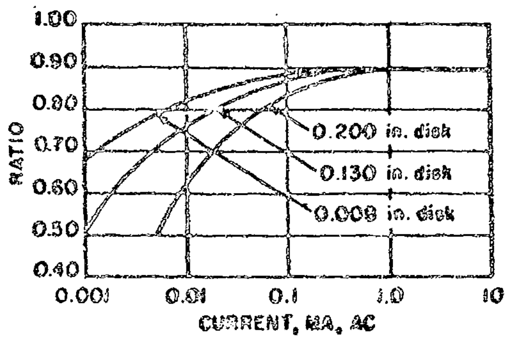


Fig. 3-14. Ratio of direct current to rms alternating current in instrument-type bridge rectifiers at various a-c levels.

Plotting the resistance values from the voltage and current data of Fig. 3-13 shows that the resistance increases at the lower values of current. Thus, for low-range voltmeters, both this effect and the effect of the fixed proportionality of the bridge tends to cramp the divisions at the lower part of the scale. Figure 3-15 shows two typical rectifier-type instrument scales. The cramping of the lower values on the 1.5-volt scale is due primarily to the increasing rectifier resistance at these values. In the case of the 1.5-kv instrument, the external swamping resistance of the order of 1 megohm makes the rectifier resistance change negligible in proportion to the total resistance of the instrument.

If the waveform is distorted, errors of several percent in terms of the true rms value may occur. This waveform error is essentially the price exacted in return for the high efficiency and simplicity of the rectifier-

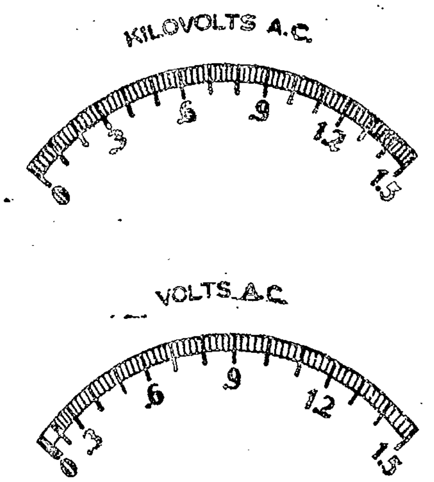


Fig. 3-15. Typical scales for high-voltage and low-voltage rectifier instruments.

type instrument. However, for a-f measurements which have random-wave form, the error is small and the rectifier type of instrument is accepted for all measurements of the level of voice-frequency circuits. For power frequencies, waveforms are rarely so poor as to give errors of more than a few percent. Arranged as a milliammeter, shunted and fed from a current transformer, the rectifier meter makes a fairly satisfactory ammeter although such a combination is less used than the iron vane type mentioned previously.

Temperature Errors. In rectifier meters these errors tend to be large, since temperature and current density in the rectifier affect both the rectifier resistance and rectification efficiency. It is possible to partially compensate the instrument for specific ranges. In general, however, temperature effects on rectifier meters are likely to be large at temperature extremes (below 0 C and above 50 C), and specific data are needed for these temperatures. Information on dry-disk rectifiers may be found in Chapter 1 of this volume.

To indicate the magnitude of the temperature errors that may exist, such errors, as they apply to a typical 150-volt instrument taking 1 ma full scale, are plotted in Fig. 3-16. Such an instrument is quite useful below about 40 C; but if operated above such a temperature, considerable errors may develop. Temperature errors for other ranges will follow different curves but will still be large at the higher temperatures; and, in general, rectifier-type instruments should not be used at temperatures above 50 C and should preferably not be used above 40 C unless the energy taken by iron-vane types precludes their use. In general, rectifier-type instruments serve their greatest usefulness in measuring a-f outputs where the high sensitivity and moderate accuracy best fits the situation.

Frequency Errors. Rectifier meters have relatively minor frequency errors in the power frequency range. In the a-f range, one may assume an average drop in reading of 1 percent per thousand cycles in standard instruments; frequency compensating networks, however, can be supplied to eliminate almost all frequency errors up to 100 kc, if necessary.

Other types of electrical measuring instruments exist, such as those operated directly by the expansion of a heated wire or strip, or operated by the bending of a heated bimetal strip. However, they are rarely found in modern electronic equipment.

To summarize the matter of errors: The precaution cited here is that the engineer should determine the time and polarity characteristics of the voltage to be measured and then select the meter most capable of measuring the voltage with a minimum of error contributed by the meter. The dynamic circuit peculiarities must be matched to the capabilities of the most appropriate meter to provide the degree of measurement accuracy adequate to the functional need for such accuracy.

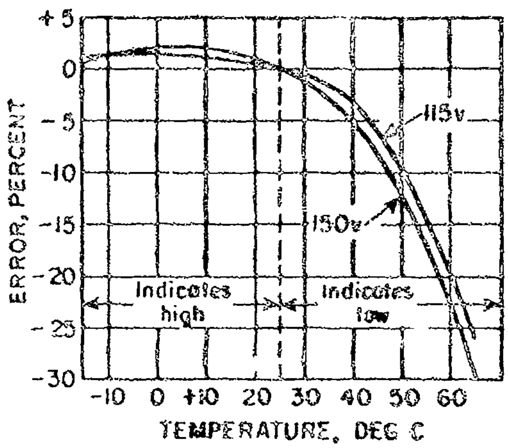


Fig. 3-16. Curves showing temperature errors of typical rectifier voltmeters (range, 150 volts; 1000 ohms per volt) with 115 and 150 volts applied; below 25 C, the instrument reading is low, and above 25 C the reading is high.

Ratio Indicators

A second important class of instruments, ratio indicators, does not measure electrical quantities as such, as in the case in the mechanisms discussed above. Instead, these instruments indicate the ratio of two currents, although the scale itself is usually marked in some other terms.

The permanent-magnet dual-moving-coil ratio indicator is made in several forms, one of which is indicated in Fig. 3-17. The two moving coils are rigidly mounted on opposite sides of a common axis and move in an eccentric airgap. Current is fed to the coils through fine filaments which have practically no control torque. When connected as shown, the coil carrying the greater current moves downward into a less dense magnetic field, while the coil with less current moves into a stronger field until the two forces balance. By its position the pointer thus indicates the current ratio, which is in turn, inversely proportional to the ratio of the resistance of the two circuits. The scale is then marked in ohms, or, if X is a resistor bulb, the scale may be marked in equivalent temperature. (See Fig. 3-18.) Using a resistor bulb containing a length of nickel wire having a resistance of 100 ohms at 25 C, take the ratio of the current through this bulb fed by a nominal battery voltage, to the current through a fixed and temperature-invariant resistor operated from the same battery. Since the resistance of the nickel wire varies approximately 1/2 percent per degree C, the current ratio will change with the temperature of the resistor bulb. Quite satisfactory temperature indicators can be made in this way. They may

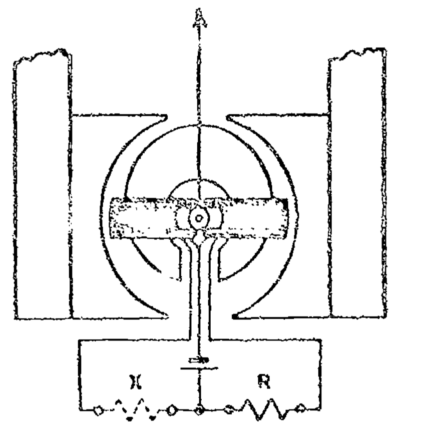


Fig. 3-17. Schematic diagram of d-c dual coil permanent magnet ratio meter with ohmmeter circuit.

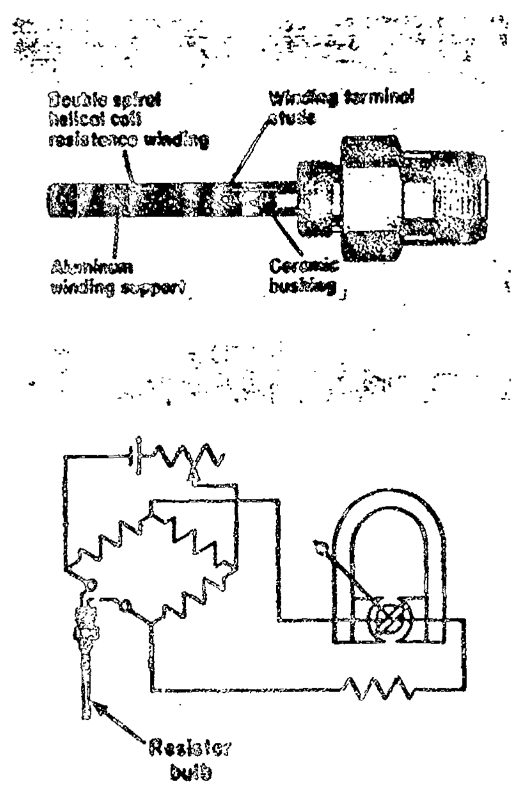


Fig. 3-18. Resistor bulb for temperature measurement (top) and circuit for temperature measurement.

have scales spanning as little as 100 C. Such instruments are widely used in aircraft for measurement of ambient air temperature, oil temperature, and intake temperature.

Other forms of dual moving-coil instruments also are made but the essential principle is the same; that is, the composite coil structure moves to a position where two torques balance. The advantage of the ratio meter is that it will operate correctly and indicate a resistance ratio practically independent of the value of the battery voltage. Ordinarily, battery voltage variation of some 30 percent above or below its nominal value is specified.

A variation of this type of mechanism for a-c use is obtained when the magnetic field is produced by a coil structure similar to that of the electrodynamometer. Here the two moving coils are usually crossed with respect to each other. Such structures are mainly used as power-factor or phase indicators in power plant control boards or in laboratory testing, and do not appear as panel instruments in normal instrumentation.

Another type of d-c ratio meter used to a limited extent for temperature indicators involves two pairs of crossed field coils and a rotating iron vane. The soft iron vane, or a short permanent magnet, will aline itself with the resultant of the two fields produced by the coils so that, in essence, this structure again is an indicator of the ratio of two electric currents. Figure 3-19 shows this construction. Since the strength of the field produced by the coils is only moderate, it is most important that this type of mechanism be well shielded. Frequently a Permalloy or Mumetal cup is used.

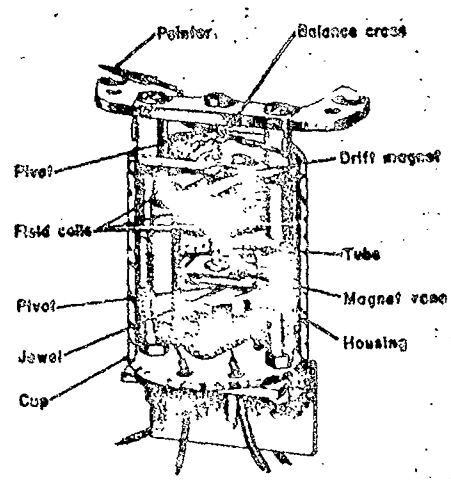


Fig. 3-19. Crossed coil iron vane ratio meter.

Frequency Indicators

Using the soft iron vane with the crossed field coils, an a-c ratio meter sometimes is used as a frequency indicator. If one of the coils is connected to the a-c line through a capacitor and the other through an inductor, the ratio of the currents through the two coils will be a function of frequency. Thus, this type of instrument can have its scale marked in cycles per second and form one important type of frequency meter. See Fig. 3-20.

In Fig. 3-20 and also for a frequency meter having a range of 56-60-64 cycles at 100-125 volts, the capacitor used is 3.3 mf and the inductance is about 4 henrys. The inductance is an iron-cored choke with an adjustable airgap allowing for some adjustment each side of the nominal 4-henry value, for obtaining the balance required to produce the wanted scale. This circuit is resonant at approximately 42 cycles. For other frequency spans different combinations of coil windings, inductance, capacity, and resistance are used to obtain the desired scale distribution.

The type of frequency meter mentioned above is largely confined to switchboard and laboratory portable instruments. Another type of frequency meter uses a group of vibrating reeds excited by an adjacent electromagnet connected to the line. Each reed is tuned to a different frequency; for example, for use at 60 cycles a group of seven reeds tuned to 57, 58, 59, 60, 61, 62, and 63 cycles might be employed. The reed in tune with the line frequency will vibrate with considerable amplitude, while immediately adjacent reeds will vibrate perhaps half as much. With the end of the reed painted white and visible through the instrument window, a long line is indicated at 60 cycles, a medium line at 59 and 61 cycles. The remaining reeds are practically stationary. Similarly, at 400 cycles reeds may be tuned every 2 or 5 cycles each side of the nominal 400-cycle mark. Provided the reed material is of good quality, not overstressed, and will not crystallize and fail in use, the reed-type frequency meter is very useful and can be made in small sizes for panel and aircraft use. (See Fig. 3-21.) However, any mechanical vibration picked up by the instrument which happens to be of the same frequency as one of the reeds will cause that reed to vibrate and may give a false indication.

Another frequency arrangement is discussed under accessories and consists essentially of a standard PMMC instrument actuated by an external combination of reactors and resistors. The actuating mechanism however, is the simple d-c type.

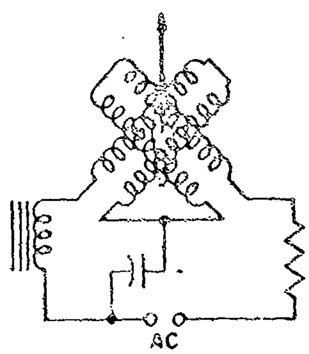


Fig. 3-20. Crossed coil frequency meter. One of the coils is connected to the a-c line through a capacitor and the other coil through an inductor.

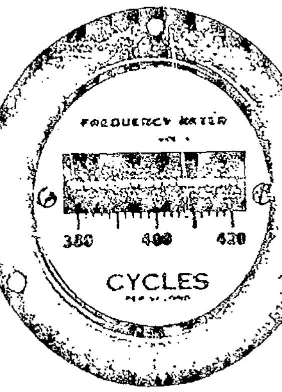


Fig. 3-21. Vibrating reed frequency meter. (James G. Biddle Co.)

Magnetized Vane Mechanism

This type of mechanism is best represented by the charge-discharge indicator in an automobile instrument panel and consists of a pivoted staff carrying a pointer and an elongated iron vane in the magnetic field of an adjacent permanent magnet. A coil of wire surrounds the vane. Current through the coil distorts the field of the permanent magnet causing the vane, staff, and pointer to rotate proportional to the current. Presently available instruments require some 30 to 60 ampere-turns for full-scale deflection, about 1000 times that required in a moving coil instrument, and draws about a watt full scale, as against a few microwatts for the moving coil type. The accuracy is only moderate as hysteresis or magnetic lag in the moving vane is usually evident, causing errors of several percent; such errors are not evident in moving coil instruments.

Because of the relatively large amount of power required and only moderate accuracy, iron vane d-c mechanisms in military equipment are generally confined to simple indicators as discussed in the next section.

Position or Function Indicators

The PMMC version of these devices is essentially a stripped assembly which may use a simple core magnet with an enclosing iron structure serving also as the mechanism frame. Intended only to indicate the presence of current, such mechanisms find wide use as indicators of circuit polarity and, in aircraft navigational instruments, operating warning flags or as simple OFF-ON indicators.

Iron vane indicators are used at times for similar purposes, where the moving system carries an iron vane and is controlled by a spring or by an auxiliary magnet. Current through an adjacent coil moves the pointer which serves to indicate a function. The moving vane also may be a magnet itself, lined up with an external magnet.

All of these position or function indicators are measuring instruments in a limited sense. Because the requirement is for an accuracy of perhaps 20 to 50 percent, they are too simplified to be considered in the category of measuring instruments as such.

GENERAL APPLICATION

In the application of electrical measuring instruments to a circuit, the question arises as to whether the instrument is influencing circuit performance. In general, energy taken by the instrument should be less than 1 percent of the total circuit energy for reasonable accuracy of measurement of circuit conditions. Thus, in a tube circuit where the plate draws 10 ma, the voltmeter should draw less than 0.1 ma or have a resistance at least as high as 10,000 ohms per volt full scale. Voltmeter resistance of 20,000 ohms per volt is about the maximum in common use, and would be perfectly safe where a plate circuit draws 5 ma or more. If the plate circuit draws less than this, plate current should be observed to determine if there is material drop in the plate current when the voltmeter connection is made. There is some safety factor since the source resistance is only a part of the total energy loss.

In general, current-measuring instruments have a drop of less than 50 mv for d-c instruments and are used in circuits of over 5 volts. When used in very low-voltage circuits (i.e., in a circuit supplied by a single dry cell), the drop through an ammeter or milliammeter at full scale may be as much as 3 percent of the total and may, in turn, reduce the current taken by the device in question by this amount. Thus, the current-measuring instrument actually measures a lower value than would exist without the instrument in circuit. Frequently, better results will be obtained in test work by using a higher range ammeter of lower resistance, even though the reading is well down the scale.

If instruments are applied as a permanent part of the circuitry, whatever energy they take is considered a part of the circuit network and they will read the true current and

voltage existing as long as they are connected. It is good practice to indicate the total voltmeter resistance in a circuit diagram showing a voltmeter since it is actually a part of the network, and this will allow for more complete circuit analysis. At radio frequency, some care is needed in introducing a thermoammeter into a circuit, particularly at frequencies above 50 Mc. The actual circuit contour may be changed by the introduction of the instrument; the smallest instrument is frequently the best because it adds a lesser value of increased circuit length and distributed capacitance.

A voltmeter can be considered simply as a shunt resistor; an ammeter as a series resistor added to the network. Their effects can frequently be evaluated in those terms.

Rectifier meters function basically because the rectifier is a nonlinear resistance varying with the current through it and a rectifier voltmeter which draws a substantial portion of the line current may well add a modulation component to the line. Thus, the VU meter with its total resistance of 7500 ohms is 25 times the resistance of the line and load resistance of 600 ohms each in parallel, amounting to 300 ohms. This value was selected as a compromise which was low enough in energy abstracted, 4 percent, to make the modulation components negligible and still high enough for adequate operation of the instrument.

In test measurements of low-power apparatus, the energy required by the added test instruments always must be carefully considered. Vacuum tube voltmeters which draw virtually no energy can be used, although the measurements are less accurate than those of instruments which are direct reading.

In general, a normal analysis of the circuit or piece of gear under test will disclose whether a major or a minor instrument-impedance effect exists. Modifications of the test procedure can then be arranged if deemed important.

Instrument Accessories

A much wider range of measurement than can possibly be encompassed by instrument mechanisms themselves, or with such items as could be included in the instrument case, is made possible by various accessories described below.

Shunts

External shunts are used for direct currents greater than 20 to 40 amp. Specification MIL-10304 for ruggedized ammeters calls for external shunts for ranges of 30 amp and higher. Essentially low-value resistors, they are made by soldering or brazing strips of manganin into heavy brass terminal blocks. These blocks serve to distribute the current into the several blades of manganin resistance material in a uniform manner as is necessary for accurate results. They also serve to convey the heat losses in the shunt blades back through the connecting cables or bus bars. From these blocks, the shunt leads carry the millivolt drop to the indicating millivoltmeter.

Manganin, an alloy of copper, nickel and manganese, is used because it does not change in resistance with temperature variation, nor does a manganin-copper junction generate any voltage when heated. Shunts of high accuracy, used in the laboratory or for the control of an industrial power plant, tend to be large and bulky. For military requirements where weight is most important, a limited design has been standardized and is described in MIL-S-61A. (See Fig. 3-22 and Table 3-2.) Because of the restricted contact area for connection to the conductors, these shunts can be adjusted only to a limited accuracy and the referenced specification calls for the voltage drop at rated current to be 50 ±0.3 mv. In the installation of such hi[illegible]current shunts (Type MSA 30-150 amp; [illegible]-600 amp; MSC 800-

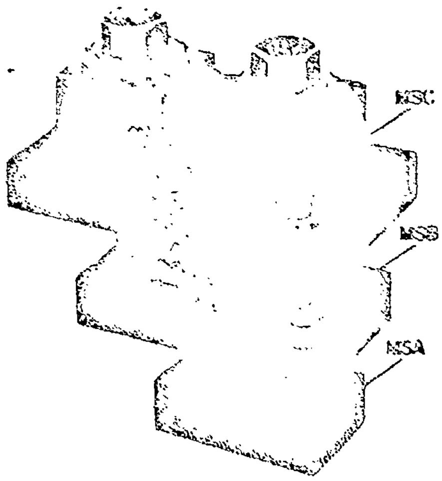


Fig. 3-22. 50 mv, lightweight-type, external instrument shunts from MIL-S-61A. See Table 3-2.

Table 3-2—50-mv Instrument Shunts
Available Values, MIL-S-61A
(See Fig. 3-22.)

(A) MSA Available Values for MSA	
Type designation	Current rating (amperes)
MSA300	30
MSA500	50
MSA750	75
MSA800	80
MSA850	85
MSA101	100
MSA151	150
(B) MSB Available Values for MSB	
Type designation	Current rating (amperes)
MSB171	170
MSB201	200
MSB251	250
MSB301	300
MSB401	400
MSB451	450
MSB501	500
MSB601	600
(C) MSC Available Values for MSC	
Type designation	Current rating (amperes)
MSC801	800
MSC102	1000
MSC122	1200

1200 amp) it is necessary that adequate and firm contact be made with the current-carrying conductor by firmly tightening the connecting bolts. This will not only improve the accuracy but it is important to remember that the power dissipated in the shunt, 5 watts per 100 amp, leaves almost entirely by conduction to the blocks and back through the main current-carrying conductors. No shunt will overheat if the connections are adequate in cross section and contact area.

Series Resistors. For potentials over the value that can be accommodated in the instrument proper, external series resistors are required. Although in special instances spools and other types of fixed resistors may be used in assembled equipment, for high potentials ferrule-terminal resistors per JAN-R-29, are used. (See Fig. 3-23 and Table 3-3.) These resistors vary in length depending upon the applied voltage; nearly 10 inches long for a range of 6 kv. They customarily have a resistance of 1000 ohms per volt (up to 6 megohms) for use with instruments having a full-scale sensitivity of 1 ma, with the scale marked in the voltage of the combination. The ferrule ends of these resistors are held in insulated clamps similar to tubular fuse clips or the equivalent. It should be stressed that the clips must be adequately insulated not only for breakdown but to eliminate any leakage currents which might parallel the current through the resistor. When tested at the voltage in use, the leakage resistance should be greater than 1000 megohms per 1000 volts rating of the resistor.

Thermoelements. Already discussed and illustrated (see Fig. 3-10) under the subject of thermoammeters, a thermoelement may be supplied as an external accessory and placed directly in the high-frequency current circuit. Short leads, preferably a twisted pair, then connect the output of the thermoelement to the instrument with which it is associated. Usually the instrument and thermoelement are calibrated together for specific leads or for a specific lead resistance.

Thermoelements of the vacuum type are also supplied for radio frequency currents below 1/2 amp down to as low as 10 ma. They are contained in a small glass bulb and their efficiency is relatively high. Vacuum thermoelements are supplied either unmounted or in various mounting forms. Figure 3-24 shows an unmounted element of this type.

Thermal Watt Converter. This device, shown in Fig. 3-11, is frequently supplied as a separate accessory for use with a d-c millivoltmeter and may take a variety of forms. Occasionally designed for application in a potted container, it may be placed adjacent to the a-c power distribution center with a twisted pair running to the d-c instrument.

Instrument Rectifiers. These have been discussed before under rectifier instruments. They are occasionally furnished as separate accessories, mounted or unmounted. Made in wide variety, they must necessarily be calibrated with the instruments to which they are connected. If the application is important, it is possible to standardize the input and output values to be interchangeable with instruments calibrated to specific values.

Instrument Transformers. These are important accessories in a-c power measurement because they are relatively small and yet perform with high accuracy. In essence, in-

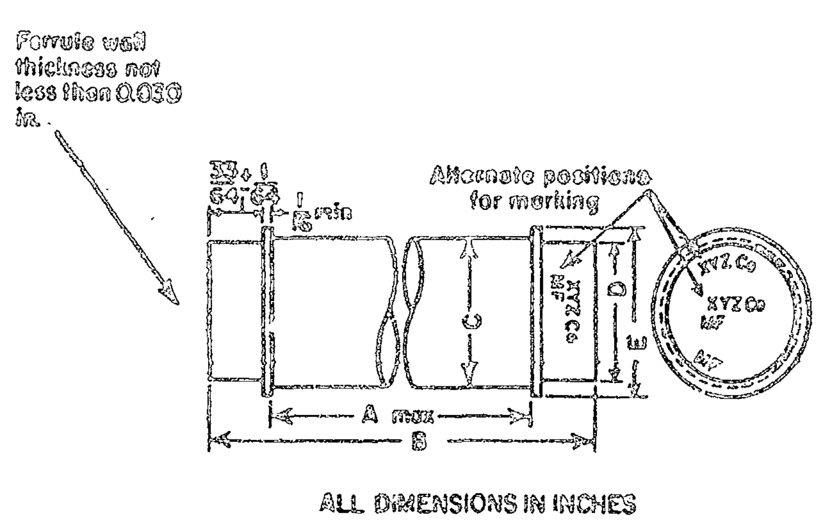


Fig. 3-23. High-voltage, ferrule-type terminal external meter resistor types, JAN-R-29. See Table 3-3.

struments transformers deliver an output that is a reduced but perfect replica of the original high current or voltage. Placed adjacent to, or in the circuit of, the high current or voltage, small wires of light weight carry the secondary replica values to the measuring instruments.

Potential Transformers. Potential transformers are not very different from small

Table 3-3 — High-Voltage, Ferrule-Type Terminal External Meter Resistor Types. JAN-R-29. (See Fig. 3-23.)

(A) Resistors Available		
Type designation	Resistance (megohms)	Rated voltage (kv)
MFA355	3.5	3.5
MFA405	4.0	4.0
MFA505	5.0	5.0
MFA605	6.0	6.0
MFB105*	1.0	1.0
MFB155	1.5	1.5
MFB205	2.0	2.0
MFB255	2.5	2.5
MFB305	3.0	3.0
MFB355	3.5	3.5
MFC504	0.5	0.5
MFC804	0.8	0.8
MFC105	1.0	1.0

* For replacement purposes for U.S. Navy only.

(B) Dimensions available (in.)					
	A	B	C	D	E
MFA	8-11/16	9-23/32	1-5/16 max 13/16 min	1-9/64	1-25/64
MFB	4-9/16	5-9/32	1-5/16 max 13/16 min	1-9/64	1-33/64
MFC	1-23/32	2-15/16	1-5/64 max 11/16 min	15/16	1

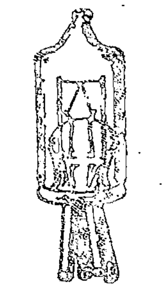


Fig. 3-24. Vacuum thermoelement for low r-f currents.

step-down transformers except that the turn ratio is accurately adjusted and special care is taken to see that the iron losses are low. Except in special devices, very few potential transformers will be needed where the power potential is less than 500 volts.

Current Transformers. With these accessories, it is unnecessary to run cables carrying the full power current to measuring instruments. Figure 3-25(A) shows a typical aircraft current transformer of the doughnut or "through" type. The main power cable passes through the opening of the transformer forming a single turn effectively. When an instrument is connected to the small terminals at the side it will receive, for example, 1/125 of the main power current, from very small values to the full rating, say 250 amp. Thus, a current of only 2 amp flows into the instrument and relatively small lead wires of almost any type can be used. The illustrated current transformer is designed for 400-cycle service as used in aircraft, for example, and weighs only a few ounces. It is, of course, satisfactory for any military use at that frequency. Similar current transformers for 50- to 70-cycle military service are somewhat larger, weighing from 8 to 16 ounces. Any of these will furnish the secondary current to several instruments if desired, the number depending on the total full-scale power in volt-amperes required by the several instruments.

When alternating current from a power source passes through the primary of a current transformer, whether it is a winding or a single-turn loop, the transformer iron is magnetized, and power is absorbed from the primary and effectively transferred to the secondary. (See Fig. 3-25(B).) A current in proportion to the primary current flows through the secondary winding and the instruments connected to it, or through the winding alone if short circuited. If the secondary is left open, however, the voltage across its terminals may rise to levels dangerous to both the operator and the transformer insulation. Thus, current transformer secondaries must be kept closed, either by connected instruments or by a short circuiting wire.

Temperature Measurement Thermocouples. These may be considered as an instrument accessory. Made in various forms to suit particular applications, they consist essentially of two wires of dissimilar metals welded together at the hot end. The most common metals used are in the nickel alloy family such as nickel-chromium for one wire and nickel-aluminum for the other, forming the commercial chromel-alumel thermocouple, which can be used to as high as 2500 F with only limited oxidation. Iron-constantan for use up to 1600 F, and copper-constantan for up to 750 F are also recognized combinations.

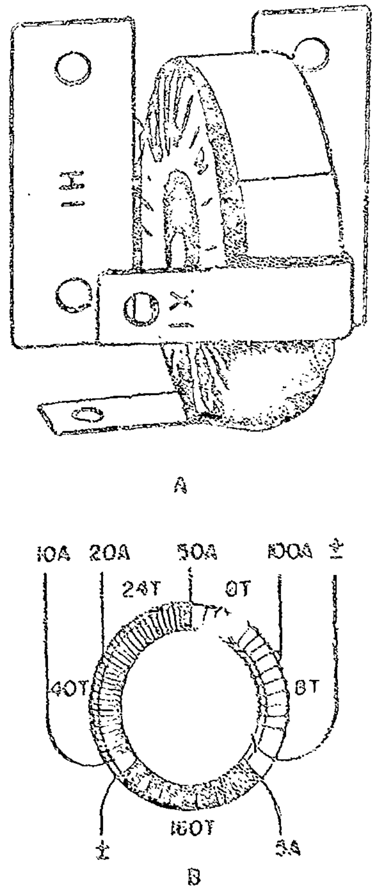


Fig. 3-25. (A) Current transformer for 400-cycle use and (B) Primary and secondary windings of current transformer showing how ratio of transformation is obtained.

It must be recognized that millivolt output for a thermocouple is a function of the difference in temperature between the hot and cold ends of the alloy wires involved. For this reason, the alloy itself, or wires of similar thermoelectric characteristics, must be carried back to the indicating instrument which, in turn, usually carries a special compensating means for adjusting the pointer position to the ambient temperature indicated on the scale. The output of a thermocouple is limited to 10 to 40 mv depending on the alloy and the temperature of the hot end. As a result large wires are desirable in both thermocouple and connecting leads to reduce the circuit resistance and allow adequate energy to reach the indicating instrument. A common military type of indicating instrument, used with the chromel-alumel couple mentioned above, is adjusted to 41.3 mv full scale with the cold end at 0 C. Voltage drop in the leads and a higher temperature for the cold end reduces this value, and a complete statement of all factors is required for appropriate calibration of the instrument. A combination of a thermocouple and an instrument is known as a thermocouple pyrometer or thermometer. In spite of the low amount of energy available, the device is most useful and quite accurate.

Resistor Bulb. An element of a resistance thermometer, this device is essentially a length of very pure nickel, platinum, or copper wire with a known temperature coefficient of resistance. In aircraft, the majority of resistor bulbs are made with a nickel wire element having a small amount of constantan wire in series for adjustment. A standard form of military resistor bulb which has a resistance of 100 ohms at 25 C to 128.86 ohms at 100 C is shown in Fig. 3-18.

A simple circuit for a resistance thermometer is shown in Fig. 3-18. A resistor bulb forms one arm of a Wheatstone bridge and, if balanced at 0 C, for example, the zero position of the pointer can also be marked this value. When the temperature increases to, say, 100 C, the bridge becomes unbalanced and the pointer will deflect an amount dependent also on the battery potential. Assuming the battery potential to have been standardized, the new deflected pointer position can be marked 100 C. Deflections at intermediate points can be determined by knowing the resistance vs. temperature characteristic of the resistor bulb. In somewhat more complicated circuits with a ratio meter as previously described (see Figs. 3-17 and 3-19), the indication will not change with moderate changes in battery potential. This arrangement is widely used in aircraft and to some degree in any military applications.

Tachometer Generator. This is another important accessory used for the measurement of rotational speed. The d-c version is essentially a small generator having a permanent magnet field. Equipped with a commutator of silver or gold alloy to prevent oxidation, and with spring-supported metal alloy brushes, the output voltage bears a fixed relation to rotational speed of the armature. The unit shown in Fig. 3-26 generates 6 volts per 1000 rpm and may be used with any appropriate d-c instrument which can have a scale marked in rpm. An a-c type is also made, usually with fixed coils and a rotating magnet. Again, the output voltage is proportional to rotational speed, and so is the frequency. Having no brushes, the life is somewhat longer; the accuracy, however, is somewhat less since the generator must be used with an a-c instrument, frequently of the rectifier type.

Tachometer generators are supplied for several types of mounting and coupling to the main shaft, including the SAE standard coupling shown in the figures. They may also be driven by gears or belts.

A brief reference is made here to another type of electrical rotary speed indicator, which does not use an instrument as such but rather involves a polyphase generator coupled to the main shaft. This generator drives a small synchronous motor at the remote point, through a three-wire connection. The synchronous motor in turn drives a speed indicator (speedometer) of the drag type used

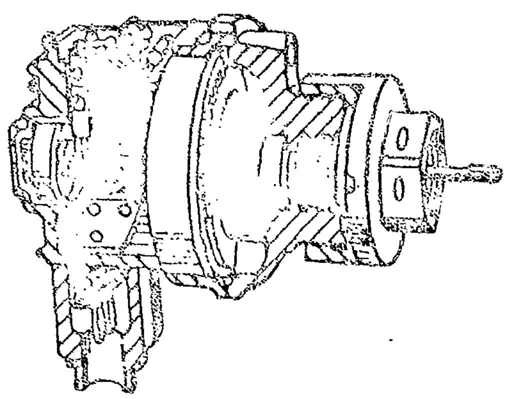


Fig. 3-26. D-C type tachometer generator for speed measurement, with mechanical coupling.

in automobiles. Widely used for aircraft engine speed, this type is somewhat less flexible than the d-c or a-c generator used with a simple indicating instrument.

Frequency Responsive Networks. These may be considered as accessories for indicating frequency on a more or less standard d-c instrument. They usually involve tuned networks and rectifiers. Where used only for frequency indications, they involve a voltage regulator network so that the resulting indication is independent of voltage variations and is a true measure of the frequency.

Figure 3-27 shows a schematic arrangement of this sort described by Smith. (3) Values are given for a typical 60-cycle center frequency transducer, useful over the range of 55 to 60 cycles. The left-hand inductance and capacitance resonate at approximately 48 cycles; the right-hand network resonates at 72 cycles. At low frequency, current in the left-hand network dominates and, at higher frequency, current in the right-hand network becomes the greater. Resistance R_3 is adjusted to equalize the currents in the two sides at the center frequency of 60 cycles; no current then flows through the meter. The four resistors are equal, and although the specific value is not important they may be typically 5000 ohms. Resistors R_1 and R_2 are again equal and may be about 1000 ohms each. The line voltage, which may vary from 100 to 130 volts, passes through a regulating transformer of a conventional type which makes the output voltage constant at a specific frequency. While this output voltage will vary with frequency, this can be calibrated into the output. The actual output of this particular arrangement is 0.5-0-0.5 ma over the span of 50 to 70 cycles, for example, and into a resistance of 5000 ohms.

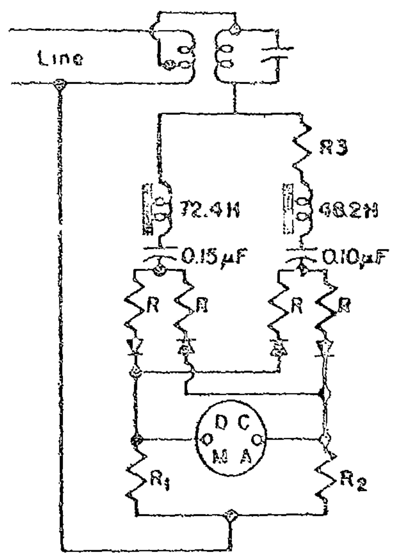


Fig. 3-27. Frequency transducer network used in the range of 55 to 60 cycles center frequency.

Similar types of frequency sensitive networks are used in conjunction with other gear, for example an a-c tachometer generator, so that the d-c output voltage is determined by frequency as a measure of the speed rather than by the voltage generated. This type of speed measurement is more accurate in many cases than the simple voltage responsive arrangement.

Other accessory devices may include position indicating rheostats, composite groups of instrument transformers, and other special arrangements specifically designed for a given requirement. Their ramifications are such that it is impossible to discuss them here in detail.

SPECIFICATIONS

Military Specifications

Numerous specifications cover the individual types of indicating instruments, shunts, and accessories; and methods of mounting instrument panels. Table 3-4 shows the military specifications covering these subjects as of March 1957.

Designation. All instruments controlled by MIL-M-6B, MIL-M-17275A, MIL-M-3823, and MIL-M-10304A are designated by the system shown below (with minor variations).

MR	18	S	001	DC	MA
Meter	Style	Color scheme	Full-scale value	Current	Units

Style. Style is identified by a two-digit number, the first of which identifies the size (and sometimes the flange shape), the second digit identifies the case material, degree of enclosure, type of panel for which it is calibrated, and flange shape (MIL-M-17275A).

Size. The table below shows the designation for the several sizes corresponding to the first digit of the style.

Digit	Diameter (in.)	Specification
0	1	MIL-M-17275A
1	1-1/2	MIL-M-10304A, MIL-M-17275A, MIL-M-3823
2	2-1/2	MIL-M-10304A, MIL-M-6B
3	3-1/2	MIL-M-10304A, MIL-M-6B
4	4-1/2	MIL-M-10304A

Case, Flange, Scale. The table below defines the meanings of the second digit in the style.

Digit	Specification	Identification
3	MIL-M-10304A	Square flange, sealed, for both magnetic and non-magnetic panels
3	MIL-M-3823	Molded thermosetting plastic or metal case, square flange, sealed, calibrated for use on nonmagnetic panel
4	MIL-M-17275A	Round flange, molded thermosetting plastic or metal case, 90-degree nominal scale, calibrated for use on a steel panel 0.09 inch thick
4	MIL-M-6B	Molded thermosetting compound case, unsealed, calibrated for use on a steel panel 0.09 inch thick
5	MIL-M-17275A	Round flange, molded thermosetting plastic or metal case, 90-degree nominal scale, calibrated for use on a nonmagnetic panel
5	MIL-M-6B	Molded thermosetting compound case, unsealed, calibrated for use on a nonmagnetic panel
6	MIL-M-6B	Molded thermosetting compound or metal case, sealed, calibrated for use on a nonmagnetic panel and on a steel panel 0.09 inch thick
6	MIL-M-10304A	Round flange, sealed, for both magnetic and non-magnetic panels
6	MIL-M-17275A	Round flange, molded thermo-setting plastic or metal case 90-degree nominal scale, calibrated for use on nonmagnetic panels and on steel panels 0.09 inch thick

Color Identification. Specifications MIL-M-6B, MIL-M-17275A, MIL-M-10304A employ the following color identification scheme; MIL-M-3823 employs "S" only.

Letter	Color Scheme
[illegible]	White dial background; black markings and pointer
B	Black dial background; white markings and pointer
F	Fluorescent markings and pointer; black dial background
S	Self-luminous markings and pointer; black dial background
M	(MIL-M-10304A) Multicolored markings

Current. The kind of current for which the instrument is designed is indicated by two letters as follows:

Letters	Current
AC	AC 60 cps nominal; 25-125 cps operating
AE	AC 800 cps nominal
AF	AC 400 cps nominal
DC	DC
RF	Radio frequency, conventional scale
RL	Radio frequency, linear expanded scale
AR	AC, rectifier-type

Units. Two letters designate the electrical units indicated by the instrument as follows:

Letters	Units
UA	Microamperes
MA	Milliamperes
AA	Amperes
KA	Kiloamperes
VV	Volts
KV	Kilovolts
MV	Millivolts
DB	Decibels

Zero Center. The end-scale [illegible] of an instrument with a zero center (or offset-zero)

is indicated by two digits with a letter between (as 5D5) which gives the decimal value of the digits as follows:

D	tenths
U	units
T	tens
H	hundreds

Thus, in the example above, 5D5 represents an instrument 0.5-0-0.5 units.

Zero Left. The full-scale deflection for meters with zero at left is indicated by three figures designating the units indicated; when the full scale is less than three figures, zeros are inserted at the left to fill out to three figures. Letter "R" between two figures indicates a decimal point. Thus, 1R5 represents 1.5.

Notes on Military Specifications

MIL-M-3823. This specification covers only the 1-1/2-inch flush-type d-c instrument having a round case of this diameter and with a front flange 1.75-inch square. These small instruments do not have enough room inside for such items as series resistors, shunts, or thermoelements, so these accessories are mounted independently and connected to the basic d-c instruments. In addition to the internal calibrated dial, this type of instrument has an external front plate, to be mounted on the instrument, on which is engraved a set of figures and a caption applying to those external accessories. The basic characteristics of this group of instruments are:

1. Accuracy—3 percent
2. Damping Factor—+2.0
3. Basic Ranges and Their Use: The basic d-c instrument used with appropriate scale plates and other accessories will give indications of volts, milliamperes, and amperes. Code MR13S001DCMA has a full-scale value of 1 ma. A similar center-zero instrument, MR13S1U1DCMA, is used for similar purposes and has a full-scale range of 1-0-1 ma. For the measurement of r-f milliamperes and amperes with external thermoelements, an instrument with a full-scale value of 10 mv is used, MR13S010DCMV. There are also instruments for 100 and 500 microamperes full scale, MR13S10DCUA and MR13S500DCUA respectively. These latter instruments may be used directly or with external accessories as may fit a particular situation.

MIL-M-17275A. This specification covers a 1-inch meter used to a very limited degree and currently available only in limited quantities. The basic characteristics of this group of instruments are:

1. Accuracy—3 percent
2. Damping Factor—+2.0
3. Range—Volts: 50 mv dc
   Amperes: 100 microamperes to 1 ma, dc.

MIL-M-10304A. Covers ruggedized instruments with round flange diameters of 2-1/2, 3-1/2, and 4-1/2 inches, and 1-1/2-inch square flange. These instruments are designed to withstand more severe shock, vibration, and humidity cycling conditions than can be tolerated by nonruggedized instruments. The basic characteristics of this group of instruments are:

1. Accuracy—2 percent
2. Damping Factors—1.5 to +2.5
3. Ranges—Volts: 1.5 volts to 30 kv, dc; 1.5 volts to 800 volts, ac (60, 400, 800 cps). Amperes: 20 microamperes to 1200 amp, dc; 10 ma to 800 amp, ac (60, 400, 800 cps); 100 ma to 30 amp, rf, ac.

MIL-I-6374(USAF). A general specification for nominal 3-inch instruments for aircraft use in making measurements in 400-cycle a-c power system. Few details are given although references are made to other supplementary specifications so that the instruments may be made applicable to aircraft use.

MIL-M-6380. A specification for an individual reed-type frequency meter with a specific range of 380 to 420 cycles at 100 to 130 volts in a flush-type case having a 3-1/4-inch diameter flange.

MIL-I-5997A. This specification covers the general requirements for the installation of aircraft instruments and instrument panels using single-unit vibration absorbers. This covers instrument panels installed in the aircraft and does not purport to cover assemblies of electronic equipment which are self-contained in themselves. To some extent this specification parallels MIL-I-7023.

MIL-S-61A. Shunts developed for aircraft use are covered by this specification. Shunt dimensions and layout are specifically covered by Standards MS-91586-7-8. These cover, respectively, shunt types MSA, MSB, and MSC of the several sizes shown in Fig. 3-22. These external shunts, with ranges of from 50 to 1200 amp, are strictly interchangeable

Table 3-4—Military Specifications for Electrical Measuring Instruments

Specification and Date	Description	1. Amendment 2. ADN 3. QPL
MIL-M-6B* 19 Feb. 1951	Panel-type 2-1/2- and 3-1/2-inch round-flange, flush mounting	1. Nr. 2, 30 Oct. 1953 2. 31 Jan. 1956 3. Nr. 12, Amend 4, 28 Feb. 1957
MIL-M-17275A* 16 May 1955	1-inch barrel, shielded and unshielded, sealed, d-c voltmeters, microammeters and milliammeters	1. Nr. 1, 25 Nov. 1955 2. 10 Aug. 1956 3. Nr. 2, 18 May 1955
MIL-M-3823* 2 May 1953	1 1/2-inch, sealed, panel-mounting d-c basic meters	1. Nr. 1, 15 Mar. 1956 2. 20 Sept. 1955 3. Nr. 2, 16 May 1955
MIL-M-10304A* 27 Sept. 1955	Panel type, ruggedized, 1-1/2-inch square, 2-1/2-, 3-1/2- and 4-1/2-inch round-flange, flush-mounting	1. Nr. 1, 2 April 1956 2. 31 May 1956 3. Nr. 7, Amend 1, 13 Mar. 1957
MIL-M-16034A 3 Jan. 1953	Switchboard and portable	1. Nr. 1, 8 Nov. 1954 2. -- 3. Nr. 7, 13 July 1956
MIL-M-16125A (1) (BuShips) 28 Sept. 1951	Frequency meters, 60 and 400 cps for ship or shore use	1. Nr. 1, 2 Nov. 1953 2. -- 3. --
MIL-I-6374 (USAF) 29 May 1953	400 cps, 2-inch	1. -- 2. -- 3. --
MIL-M-6360 (USAF) 13 Aug. 1953	400-cycle reed-type frequency meters, flush case, 2-1/4-inch round	1. -- 2. -- 3. --
MIL-A-6370 (USAF) 6 July 1953	Ammeters, 400 cps, 0-250 amp	1. -- 2. -- 3. --
MIL-V-6753A 23 Mar. 1956	0-150 volt, 400 cps	1. -- 2. -- 3. Nr. 1, 10 Apr. 1956
MIL-A-6762A (ASG) 24 Dec. 1953	D-C voltmeters, 50-mv ammeters	1. Nr. 2, 15 Nov. 1955 2. -- 3. Nr. 0, 23 Nov. 1953
MIL-S-61A 24 April 1953	External, 50-mv lightweight shunts	1. Nr. 1, 4 April 1956 2. 15 Mar. 1956 3. Nr. 21, 18 Dec. 1956
MIL-I-1361A 14 May 1953	Shunts, resistors, transformers, accessories	1. -- 2. -- 3. Nr. 1, Amend 3, 30 Nov. 1956
JAN-R-29 13 Nov. 1944	External series resistors, ferrule terminal, high voltage	1. Nr. 5, 3 Aug. 1953 2. 20 Mar. 1956 3. Nr. 16, 21 Nov. 1956
MIL-I-7028 11 Oct. 1950	Installation of meters and meter boards	1. Nr. 1, 8 Nov. 1951 2. -- 3. --
MIL-I-5997A (USAF) 12 July 1954	Installation of meters and panels using single-unit vibration absorbers	1. Nr. 3, 2 May 1956 2. -- 3. --

*Coordinated tri-service specification.

and have a voltage drop of 50 mv at their rated current. While the accuracy rating is 0.6 percent when hot, 110 ± 5 C, a somewhat wider tolerance than allowed on commercial shunts of larger size, these shunts are adequate for use with panel instruments.

JAN-R-29. This specification covers series resistors for high-voltage instruments in three different sizes, MFA, MFB, and MFC, having ranges from 0.5 to 6.0 megohms for use on 0.5 to 6.0 kv. The specification gives the dimensions in some detail along with test requirements. These resistors are widely used for both military and commercial applications. Similar commercial versions exist having values as high as 30 megohms for use on 30 kv. These resistors are superior to any other type for voltages over 1000 and even for commercial work where no specification requirement exists, these types are dominant. Their general form is as shown in Fig. 3-23.

MIL-M-16034A. Instruments generally larger than the panel type, along with portable testing instruments, are covered by this specification originally sponsored by the Navy Department. The switchboard instruments covered are rectangular-front instruments, nominally 4-1/2 inches square, with long scales spanning approximately 250 degrees; and 6-inch rectangular instruments with nominal 90-degree scales. A-C and d-c voltmeters and ammeters, and r-f ammeters are covered. Portable instruments are listed in the 0.25 percent accuracy class for both a-c and d-c types and in secondary accuracy class of 0.5 percent for d-c instruments and 0.75 percent for a-c instruments. Details as to scale length and the effect of various influences are listed in supplemental specification sheets.

MIL-M-16125A(1). As with the previous specification, the instruments covered are of the switchboard and portable types for ship or shore use. Dial-type meters are covered as well as vibrating reed meters; the latter are confined to shore use. The size and kind of instruments covered are the same as in MIL-M-16034A; types are for nominal 60 or 400 cycles.

MIL-I-1361A. Accessories covered by this specification are in a somewhat higher accuracy class than those items previously referred to for use with panel-type instruments, for example, shunts are to be within 0.25 percent. Current transformers are covered having a ratio-error limit of 0.25, 0.5, and 0.1 percent for three different classes and at full rated current.

The last three specifications covering the larger switchboard and portable instruments may be referenced where such instruments are required for laboratory use or for important ground installations. They will rarely be used in conjunction with electronic equipment for mounting in a plane.

Commercial Specifications

There is one dominating industry standard, the American Standard for Electrical Indicating Instruments, ASA C39.1-1955. Since this specification was developed by a working committee reporting back through representatives from many professional societies and trade groups, it represents the composite thinking of a large number of experts. Panel instruments in the 1.5-, 2.5-, 3.5- and 4.5-inch flange diameters are shown in some detail; the smallest size with a rectangular flange only and the larger sizes with both round and rectangular flanges. Instruments for a-c and d-c as well as r-f ammeters are covered. Similarly 4-1/2- and 6-inch switchboard instruments are shown in their several ramifications, including wattmeters and power-factor meters. Portable a-c and d-c ammeters, voltmeters, and wattmeters are listed with scale lengths of 12 inches for a rated accuracy of 0.1 percent, 5 inches for a rated accuracy of 0.25 percent, 3.2 inches for 0.5 percent, and 2.5 inches for 1 percent. A 2-percent accuracy class with a 1.5-inch minimum scale length also is tabulated for ammeters and voltmeters. The specification is so complete that it should be available to all those interested in specifying instruments.*

Since the ASA specification was sponsored by the American Institute of Electrical Engineers, the Institute of Radio Engineers, the National Electrical Manufacturers' Association, the Radio-Electronics-Television Manufacturers' Association, and others, those organizations have no other basic instrument specifications. There are some NEMA specifications on instrument transformer dimensions and sizes. Perhaps the only supplemental specification of importance in the electronics field is the ASA specification on the VU meter, ASA C16.5-1954, sponsored by the IRE; the specification was originally printed in the IRE Proceedings, Vol. 42, No. 5, May 1954 in

* Available from the American Standards Association, Inc., 70 East 45th Street, New York 17, N. Y. Price $2.00.

an article titled "American Standard Practices for Volume Measurements of Electrical Speech and Program Waves."

The major change in the 1954 specification from the previous issue of 1942 was in the use of a matching transformer or network to take care of line impedances other than 600 ohms, originally the only value shown.

A typical monitoring VU meter type is shown in Fig. 3-28. The specification covers the requirements for instrument ballistics whereby the dynamic performance of all such instruments will be basically the same. There are no military specifications on a VU meter as such. For military applications, a DB meter based on 1-mw level is sometimes used and is generally acceptable.

Refer also to the Master Test Code for Electrical Measurements in Power Circuits, AIEE No. 552, November 1955, and ASME PTC19.6, 1955. The Test Code is not a specification, but discusses laboratory instruments for making performance tests on equipment, and is an effective text book on making such measurements.

The large manufacturing companies have equipment specifications, although in many instances they simply list and repeat the items in ASA C39.1, with such supplementary information as the part number used for that manufacturer. Deviations from the requirements set by the standard specifications previously referred to are rare, largely because of the existence of these standards and because special instruments are so expensive to process in small quantities. On the other hand, special orders for instruments in quantity, involving requirements where the special features will result in simplified use of the associated electronic equipment, are quite acceptable to the instrument manufacturer provided that the expense of special tooling can be written off by agreement between the parties concerned.

INSTRUMENT SELECTION

In addition to the numerous aspects discussed up to this point, still other factors enter into the final selection of an instrument for a given job. Some of the more important factors are discussed below.

Cases

Instrument cases are made of either plastic or metal; wood cases are used occasionally for portable or laboratory instruments.

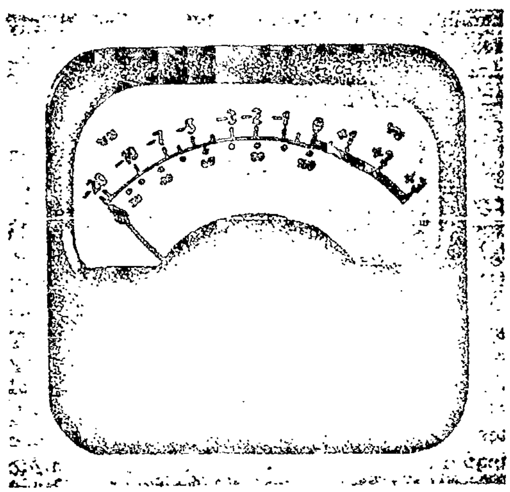


Fig. 3-28. VU meter emphasizing VU calibration.

Metal cases have one advantage; if made of iron, they will serve as magnetic shields for the internal magnetic system. By the same token, they may affect unshielded instruments or a magnetic compass in close proximity. Brass or aluminum cases are used occasionally where a nonmagnetic metal is required or where light-weight aluminum is needed. Most metal cases are painted although some aluminum cases are oxidized and finished in black. Disadvantages of using metal cases include scratching of the finish, cost of metal, and the difficulty of obtaining metal in times of high priority.

Plastic cases on the other hand are widely used, do not need to be finished, and serve as excellent insulators so that they may also carry portions of the instrument mechanisms directly. Most commercial instrument cases are molded from a phenolic resin although transparent materials in the methacrylate or polystyrene types are used in commercial forms where appearance is dominant. Phenolic cases expand and contract much more than metal if exposed to wide variations in temperature and humidity. Therefore, so-called "single cycle" phenolic resins, which exhibit these changes in a minimum degree, are preferred for this purpose.

Windows

Glass windows are widely used and are satisfactory. Usually held in place with a sealing compound and a spring ring, the seal is adequate unless exposed to wide changes in barometric pressure along with changes in

humidity and temperature. When hermetically sealed instruments are required, glass windows can be used with a metallized edge and soldered into the metal case.

Plastic windows are being used more often and, if appropriately sealed with gaskets, appear to be quite satisfactory. On plastic windows, however, static charges tend to build up which may attract the pointer and give false indications. An antistatic treatment of the plastic is usually necessary. An instrument carrying a plastic window can be readily checked for static charge by rapidly rubbing the face of the instrument with a silk or wool cloth; if the plastic is antistatic treated, the pointer will not remain off zero for more than a second or two. This test should be made when the instrument is dry; in humid weather the instrument should be conditioned in a dry atmosphere for 48 hours. While plastic will scratch, apparently this has not proved to be a problem in its use particularly with the harder formulations available today. Scratches frequently can be made nearly invisible by applying a bit of wax to the surface.

The window thickness will run between 1/16 and 1/8 inch; 1/10 inch is common. The window should be stiff enough to avoid deflecting inward in any normal use. Ordinarily, the distance between the inner face of the window and the scale plate will be 1/4 inch with a minimum of 0.2 inch and a maximum of 0.38 inch, except in special instances where a greater distance is required for some special reason.

Instrument Size

Case size is important; a large size takes up panel or bench room, a small size makes reading of the divisions difficult. The nominal 3-inch size is satisfactory for the common 2-percent panel instrument. If conditions are crowded, the rectangular type of front face saves room by reducing the mounting flange at the sides, top, and bottom. Such rectangular face instruments are listed by most makers.

Never use the 1.5-inch instrument where measurements must be made with any considerable degree of accuracy. Because it is supplied with only 10 divisions, it is difficult to read the instrument to the 3-percent nominal guarantee. These small instruments should be used only where it is impossible to use the 2.5- or 3.5-inch size, or where an indication only is needed of such items as plate current or r-f current. The 1-inch instruments covered by one of the specifications are made by only one company and have never found much favor in electronic equipment because of the sheer difficulty of reading the indications.

Generally, instruments larger than the 3.5-inch size are used only where they must be read at a distance. They may, however, have some place in ground equipment and are used to a certain extent in test sets.

In summary, instruments for electronic equipment are mostly of the 2.5- and 3.5-inch flange diameter, and are available in these sizes for direct current and voltage, a-f current and voltage (rectifier type), r-f current (thermocouple type), and alternating current (iron vane type) for use on 60, 400, and 800 cycles. Of lesser importance are the 1.5- and 4.5-inch instruments available for direct current and voltage, as well as audio frequency and radio frequency; they are not generally available as a-c instruments for power frequency. The 1-inch instrument is available only for direct current and voltage. DB and VU meters are basically rectifier-type instruments with special scales. Instruments for the measurement of frequency and other less common needs are limited in their types.

Scales

Instrument scales are discussed in some detail because there is usually a considerable choice of instrument scales and ranges for a given application.

The length of the scale is, of course, a function of the size of the instrument. The cost of a 1.5-, 2.5- or a 3.5-inch instrument will be almost the same; basically, all use the same or a similar mechanism, but there is a difference in overall accuracy. Even though the 2.5- and 3.5-inch instruments are both rated at 2-percent accuracy in terms of full scale deflection, the greater scale length of the larger instrument will lead to greater accuracy in the actual reading of the indication. Most specifications allow an instrument pointer to ride a maximum of 0.1 inch above the scale surface and parallax errors will inevitably come into play unless great care is taken to view the pointer from a point perpendicular to the scale. In any event, with a given amount of parallax the 2-inch minimum scale length on the 3.5-inch meter will give a smaller reading error than the 1.5-inch scale of the 2.5-inch type.

Thus, the 3.5-inch instrument is recommended where readings are to be taken to the

full accuracy guaranteed for the instrument, unless panel space is so restricted that a smaller instrument is deemed appropriate.

A tabulation of scale lengths covered by the several military specifications is given in Table 3-5. The above discussion applies

Table 3-5—Minimum Scale Length Requirements

Specification	Meter size (flange diameter, in.)	Minimum scale length requirements (in.)
MIL-M-6B	2.5	1.5
	3.5	2.0
MIL-M-3823	1.5	1.0
MIL-M-17275A	1	0.75
MIL-M-10304A	2.5	1.5
	3.5	2.0
	4.5	3.25*

*From supplementary documents.

to instruments for a subtended angle of about 90 degrees. So-called long-scale instruments, where the pointer rotates over about 270 degrees, are available in the larger switchboard sizes and are covered by specifications on switchboard instruments. They are available in only limited number and usually for direct current only in the 3-1/2-inch size and smaller; military specifications in general do not contemplate instruments of this type. However, they are used widely on the aircraft panel for navigational purposes and as engine instruments for measuring temperature, air speed, rpm of the engines, and for special purposes such as distance indicators. In general these long-scale instruments are basically less accurate than the 90-degree instruments but more readable. They tend to be more expensive and take more power to operate. They represent a limited class with limited performance and, while valuable in special instances, are rarely used in the broad variety of electronic equipment in the military establishment.

Having a given size of instrument with a given scale length, the number of divisions is frequently in question. In general, divisions should not be closer than about 0.03 inch for panel or portable instruments, thus being about as close as the eye can differentiate. With a 1.5-inch scale, common practice is to use a maximum of 40 divisions and thus, to cover all scale range possibilities, it may be said that the 1.5-inch minimum scale length of a 2.5-inch meter should have between 20 and 40 divisions. Similarly, on the 2.0-inch minimum scale of a 3.5-inch instrument, the number of divisions should be between 40 and 75. As previously indicated, the 1.5-inch instrument is specified to have 10 divisions.

The 4.5-inch instrument would also carry from 40 to 75 divisions since a great number of divisions are not needed with the 2-percent basic accuracy of the instrument and good visibility is the prime need. This size is also used in many test sets in a horizontal position with a multiplicity of scales; the large size allows for both d-c and rectifier-type a-c scales, an ohmmeter scale, and a scale in db, all without undue crowding.

Large switchboard instruments, to be read from a distance, are generally supplied with from 30 to 75 divisions, the divisions being rather coarse so that they do not blur. Portable instruments, on the other hand, will run up to as high as 150 divisions on a 5-inch scale, maintaining the minimum of 0.03 inch between divisions since they are used for close readings.

Figure 3-39 shows a variety of scales, actual size, representing the minimum and maximum number of divisions for the several sizes.

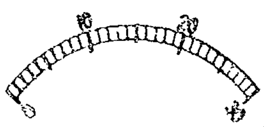
The spread given above in the number of divisions is necessary to cover all scale ranges since it is mandated in numerous specifications that each division represent 1, 2, or 5, or a decimal multiple or submultiple thereof, of the quantity measured. Thus, for a 3.5-inch meter, a 150-volt scale should have 75 divisions with 2 volts per division. A 300-volt scale should have 60 divisions with 5 volts per division. A 5-amp scale should have 50 divisions with 0.1 amp per division.

Requirements for coarser or finer scales than contained within the limits will usually be considered special and will be more expensive. Scales for instruments for military use that are to be made with fluorescent or luminous ink must necessarily be somewhat coarser and ordinarily will have about half as many divisions as the above figures for readability. It is a fallacy to believe that a large number of divisions will result in greater accuracy. Many studies made with regard to the accuracy of reading instruments all indicate that scales within the above listed limits are best from all points of view.

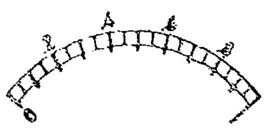
There is some variation in the details of scales supplied by various makers and they represent, in the last analysis, rather minor variations in utility. It is believed that the optimum scale has divisions probably about

For 2.5-inch D-C Instruments

A-40 divisions, maximum number, figured for 2 units per division, 10 units per cardinal division.



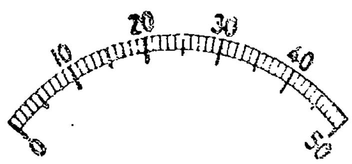
B-30 divisions, optimum number figured for 1 unit per division, 5 units per cardinal division.



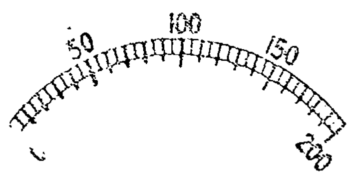
C-20 divisions, minimum number, figured for 0.05 unit per division, 0.1 unit per cardinal division.

For 3.5-inch D-C Instruments

D-75 divisions, maximum number, figured for 2 units per division, 10 units per cardinal division.

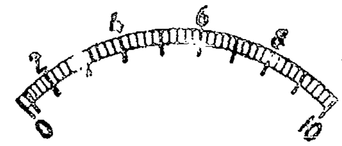


E-50 divisions, optimum number, figured for 1 unit per division, 5 units per cardinal division.

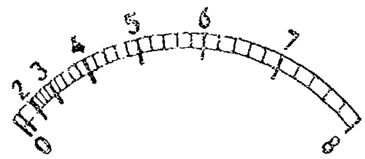


F-40 divisions, minimum number, figured for 5 units per division, 10 units per cardinal division.

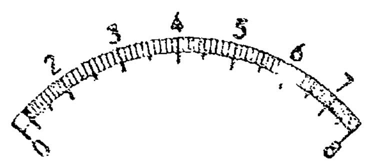
For 3.5-inch A-C and R-F Instruments



G-Equivalent 50 division scale, cramped at left, for typical iron vane instrument.



H-Equivalent 40 division scale, following square law for r-f ammeter with regular pole pieces.



I-Equivalent 80 division scale for linear expanded r-f ammeter with cut pole pieces.[a]

[a]An 80-division scale is used here because the "Standards of Good Engineering Practice" of the Federal Communications Commission requires that linear expanded scale r-f ammeters have a minimum of 50 divisions. Thus, such instruments carry 50 to 80 divisions depending on range.

Fig. 3-29. Typical panel instrument scales.

0.05 inch wide, or a median value between the referenced limits.

Scales are evenly divided on practically all d-c instruments as a result of the uniform air-gap flux density through which the moving coil rotates. In special instances, the airgap can be made nonlinear, resulting in a nonlinear scale distribution; if the distribution is logarithmic, this can be arranged to give more evenly divided logarithmic values of, for example, db levels.

Thermocouple r-f ammeters necessarily have a nonlinear distribution because of the square law characteristic resulting from the basic characteristic of the thermal converter. Here again, by cutting the pole pieces, a portion of the scale can be made more linear; and this arrangement is usually known as "linear expanded type." Iron vane instruments, dynamometer instruments, and other special types frequently have nonlinear scales. Although the linearly divided scale may appear to be simplest and best, the designer has little choice if the basic instrument mechanism is nonlinear. To straighten out the characteristic is only occasionally possible, and always expensive.

Partly because of the fact that nonlinear scales are usually most nonlinear in the lower portion, it is considered good practice to select an instrument range where the majority of the readings will be about 3/4 of the top scale value. Thus, for 115 volts, a 0-150 voltmeter is probably optimum and allows for some overvoltage to be indicated. One will rarely go wrong in selecting a full-scale range from 20 to 60 percent above the highest normally expected reading, in this way maintaining the ability to read minor overloads and still have good scale readability in the working range.

Mirror Scales. Instrument indications should always be observed with the eye directly perpendicular to the instrument scale and over the position of the pointer tip. If viewed at an angle, the apparent position of the pointer with respect to the scale will be at variance with its true position. To assist in eliminating this effect of reading at an angle, called the effect of parallax, high-accuracy portable instruments are supplied with a thin knife edge pointer and a mirror scale. In reading such instruments, the eye should be positioned so that the pointer completely obscures its reflection in the mirror since this will place the eye truly perpendicular to the scale and make it possible to take accurate readings. In general, mirrors are only supplied on portable instruments having a rated accuracy of 1 percent or better.

Multiscale Instruments. Since the basic mechanism of an instrument can be used for a variety of voltage ranges through the use of different values of series resistance, a high-scale voltmeter can have its resistance tapped for lower voltage ranges with the taps brought out to appropriate terminals. Similarly, multirange milliammeters can be made by tapping the shunt resistance, and the two can be combined along with the use of the mechanism as an ohmmeter. Thus, volt-ohm-milliammeters are readily produced by associated resistance circuitry and the taps are frequently selected by a rotary switch or other switching means. In turn, a multiplicity of scale figures are required to cover the several ranges; and in the case of a combination volt-ohmmeter, for example, where the divisions are different for the two functions, two or more sets of divisions may be required. Such instruments are very useful in test work, but great care is required to select the appropriate range so that overloads may be avoided as well as to read on the scale associated with the range being used. Occasionally multirange panel instruments are used, and most any desired combinations can be built with appropriate resistance networks and switching. The great hazard here is that readings may be taken on a range different from that connected to the circuit. Panel instruments are usually single range with a single scale for a specific purpose.

Pointers

In connection with scales, mention should be made of types of pointers. While most panel instruments carry a pear-shaped tip, the requirements for rugged construction have made the so-called lance tip rather widely used. The pointer itself is simply a piece of thin-walled seamless aluminum tubing with the tip pressed flat and cut to a point. Pointer tips should be sufficiently large to be readily seen, with a pointed end of the same width as the scale divisions so that an appropriate accurate reading can be made. Luminous pointers occasionally are required for electronic equipment and used widely on the aircraft panel, and are made to have a width of up to 0.1 inch, so that a considerable amount of luminous material can be carried to identify the pointer in dim light. Large switchboard instruments have bold indicators since they are made to be read at a distance; portable in-

struments carry fine knife-edged pointers for close reading either directly, or with a magnifying glass.

Most scales are mat white in finish, obtained by a fume-proof lacquer on metal; portable instruments carrying hand-drawn scales are frequently on bristol board cemented to metal. In this case, the metal is usually polished to serve as a mirror through an aperture adjacent to the scale. If the pointer is alined with its reflection in the mirror, the eye is truly perpendicular to the scale.

On the other hand, when one is operating at night and the eye is dark-adapted as in an airplane or on maneuvers, the glare from the white finish makes the scale nearly unreadable. Under these conditions, black background scales with white or luminescent divisions, figures, and pointers will prove most useful. Thus, the selection of white or black backgrounds depends, basically, upon the existing general illumination. If it is bright with bright surroundings, standard white scales are indicated; in dim light, black scales should be selected.

Occasionally, other colors are used. Red divisions or blocks on the scale are used to indicate special calibrating points or points of adjustment; red blocks are sometimes used to indicate an overloaded condition. The buff background scale of the VU meter was selected to moderate the glare of the scale where continuous observation of the scale is required for long periods of time.

Other scale markings, captions, nominal full-scale data, and the like are required on the scale but only the unit measured should be in large type (i.e., amperes, volts, etc.). Supplementary information, military part numbers, the maker's name and model number should be smaller and placed away from the main scale arc so that they do not interfere with clear readability of the divisions.

Most instruments have the zero at the left and progress clockwise. Occasionally, special aircraft instruments are rotated with the zero at some odd position for the primary purpose of having all pointers on the instrument board horizontal when conditions are normal. These are special conditions and the majority of instruments deflect clockwise from left to right across the vertical centerline.

Instrument Shielding

Electrostatic shielding is needed only where there is a large difference of potential—over several hundred volts—between the instrument mechanism potential and adjacent conductive parts. Thus, a milliammeter in the high potential circuit of a radio transmitter should be shielded by a metal case unless, in operation, there are no effects of its high potential to ground. In general, when the metal case is connected to an established potential, the mechanism is shielded from electrostatic effects. Shielding need be considered only where plastic cases are used.

Magnetic shielding in an instrument eliminates: (1) the effect of strong external magnetic fields on the internal mechanism field, (2) the effect of mounting on an iron panel which may reduce the internal mechanism field (both of these effects will cause errors in the indication), and (3) the effect of the external leakage field on the mechanism of other instruments such as a magnetic compass.

An external field of 5 gauss may affect an unshielded d-c instrument as much as 2 percent; lesser fields can usually be disregarded. Heavy fields may occur next to a magnetron, and occasionally a very heavy choke will have a sufficient external field to affect an a-c instrument in close proximity.

The allowable effect of an instrument leakage field on an aircraft compass is spelled out in detail in specifications for aircraft instruments. However, the effect of an unshielded d-c instrument is usually small at distances beyond 3 feet so that this mainly applies only to those instruments that are mounted on the main aircraft instrument panel and to those that may be adjacent to a compass. Miscellaneous electronic equipment mounted elsewhere in aircraft or in ground equipment can generally be provided with instruments without regard to extraneous effects on other items.

Magnetic instrument panels tend to reduce the air-gap flux in an unshielded d-c instrument if the iron or steel panel closely surrounds the meter. Specifications take account of this, and unshielded instruments may be obtained adjusted for mounting in magnetic panels having a nominal thickness of 0.09 inch (an average of 1/16- and 1/8-inch panels). The effect of a metal panel of this kind is to reduce the reading roughly 3 percent if the instrument is otherwise unshielded.

Iron cases will shield the instrument from the effect of a metal panel or an extraneous field. Some plastic-cased instruments have a

ring of iron inside the plastic, and some instruments are inherently self-shielded. The ruggedized instruments are specified to be magnetically shielded and are usually furnished in iron cases.

In general, the matter of magnetic shielding must be recognized, and suitable instruments specified as compatible with any existing magnetic panels, external fields, or compasses mounted nearby.

Zero Corrector

Because the control spring on an indicating instrument, against which the electromagnetic force is measured, must be made of nonmagnetic material, a bronze alloy is ordinarily used. But even beryllium copper springs may show a permanent set after having been subjected to the shocks of shipment, and, in spite of the best metallurgical treatments, bronze spring materials will drift with time from their initial free position. A zero corrector, therefore, allows resetting the pointer to zero as these effects become evident. The amount of correction is usually limited to about 3 degrees on the scale arc. Springs rarely shift this maximum amount if properly manufactured.

However, a zero corrector is difficult to design into a small instrument or one which is to be sealed and, as a result, zero correctors are ordinarily not supplied in the 1-inch instruments. MIL-M-6B requires all unsealed instruments to have zero correctors but does not require them on sealed instruments. Ruggedized instruments per MIL-10304A are not required to have external zero correctors on the 1.5-, and 2.5-, and 3.5-inch sizes, although many manufacturers supply them as good instrument practice. The 4.5-inch instruments, however, under MIL-10304A, are required to have zero correctors. All of the larger sized instruments and portable instruments ordinarily carry zero correctors.

All of the above applies to instruments having a free zero. Certain types of frequency meters, power-factor meters, ratio meters of any kind, and instruments having a suppressed zero are not furnished with an external adjustment of this type, since there is no free zero to correct

Mounting

Provisions are generally furnished with panel instruments for proper mounting. For round-flange flush-type instruments, round-head black-finished screws with appropriate nuts and washers are called for in the military specifications and are ordinarily supplied on commercial versions as well. For the rectangular-flange and some other types of instrument, there are frequently furnished nuts and washers, and studs molded in the flange to function as permanently affixed screws.

Instruments which carry special aircraft flanges may have brass inserts in the corners, or sheet-metal locking nuts may be specified. There is also the so-called clamp-type case where the metal instrument case terminates in a grooved flange at the front on which can be locked a separate mounting flange for attachment to the aircraft instrument panel. No details of these arrangements are shown here because such instruments are generally not used except on the main instrument panel for navigational and engine instruments.

In the mounting of instruments having a flange, care should be taken not to pull up on the mounting screws to the point where a warped or uneven instrument panel would cause the flange to break. Thin, soft rubber gaskets sometimes are used under the instrument flange to seal the interior of the box or device on which the instrument is mounted from entrance of dust. Similarly, a somewhat heavier gasket may be used in conjunction with the ruggedized instruments to form a completely watertight seal. Instruments of this class are generally furnished with much heavier metal flanges which will allow for pulling up the instrument against the gasket without distortion.

While panel meters are customarily mounted on a vertical board with the axis horizontal, experience and study have indicated that bearing friction is much less if the instrument axis is vertical, since in this position the bottom pivot rotates on its extreme tip and the upper pivot becomes merely a guide bearing. For this reason, the more precise portable instruments generally are operated horizontally with a vertical axis. If panel instruments are used in a precise application, best results will be obtained if the face is horizontal and the axis vertical.

Mounting is concerned with friction effects only. Vibration and shock effects appear to be little different whether instruments are mounted in a vertical or horizontal position. Any instruments which are to be transported from one location to another in a car or on a train should be placed upside down on the

cushions. In this position, any shocks will be absorbed by the upper bearing, while the lower bearing, which is the critical one, floats without being damaged by pounding. The upper bearing is, in use, the guide bearing, and minor deformations caused by the shock of travel will rarely cause difficulty in actual use in a normal position.

Terminals

There are many types of terminals. Most commercial instruments are furnished with threaded terminal studs, and the various specifications cover the numerous sizes. It is good practice to clamp lug-type solder terminals under the nuts and washers of each terminal and to solder circuit wires onto that terminal. Placing loops in fine wires for clamping on an instrument terminal is generally frowned on unless the wire is No. 16 or larger.

Ruggedized instruments are frequently furnished with solder terminals; solder terminals emerging from the instrument case are mandatory in some instances. Assemblers of electronic equipment are generally prepared to work with solder terminals. Switchboard instruments of larger size, however, are always furnished with threaded terminals and, of course, portable instruments are supplied with binding posts appropriate for the current and voltage of the particular instrument circuit involved.

Instrument terminals are for connecting purposes only. It is considered bad practice to hang another component on these instrument terminals unless the component is an instrument accessory specifically designed for that purpose. Further, when conn[illegible]ting heavy wires to instruments as required for current circuits, the connecting wires should be either flexible or, if solid, formed into a loop so that the movement of the wire itself, transmitted from other equipment to which the wire may be connected, will not cause continuous vibration of the terminal [illegible] resultant damage. In a particularly bad case, a short stiff wire from a large tuning inductance was clamped under the threaded terminal of an r-f ammeter. On vibration test, the coil vibrated in resonance and completely destroyed the instrument by transmitting this motion to its terminal stud and breaking the internal connections.

Where solder terminals are used, the circuit wire should be looped over the solder terminal and the actual soldering operation should be sufficiently rapid to avoid the transmittal of heat through the terminal into the interior of the instrument. Even though the specifications state that the internal connections shall not open with a soldering iron used externally, it is deemed good practice to make the external soldering operation as rapid as possible.

ENVIRONMENTAL PROBLEMS

In addition to normal hazards to which any sensitive device is subjected, electrical measuring instruments must be able to withstand certain degrees of vibration, shock, variations in temperature and humidity, overload, and other factors. Difficulties during World War II, when conventional instruments were damaged by fungus and high humidity as well as the shocks and vibrations of normal military service, led to the development of the ruggedized instruments now available. They should be specified and used when conditions are likely to be more hazardous than conventional instruments can tolerate.

Temperature

Conventional instruments are designed and built to operate from the freezing point to perhaps 150 F without danger, except that they may absorb moisture at one temperature and condense that moisture on internal parts when cold. Higher temperatures require special handling of the cements used, with 185 F probably being the top allowable temperature for the ruggedized instruments.

Altitude and Pressure

In unsealed instruments high altitude and rapid pressure changes may cause moist air in the instrument to condense and possibly result in corrosion and other difficulties. It is to be noted that an air-damped instrument loses damping rapidly as the pressure is reduced. Sealed instruments, of course, are unaffected.

Humidity

Humidity, when over 90 percent, can cause plastic cases to swell and loosen, and cause corrosion in most varieties of unsealed instruments. Where continuous high humidity or cycles of it may be encountered, sealed instruments, including the ruggedized type, are the best answer.

Shock and Vibration

The question is frequently raised as to the life of a measuring instrument. Experience has indicated that unless subject to electrical or mechanical overload resulting in thermal or mechanical failure, the breakdown of a rectifier or the burning out of a therm. element or a spring, the life expectancy of an instrument is many years. Pivot wear, as such, rarely causes difficulty and instruments have been inspected which have indicated the individual dots and dashes on a telegraph system for many years with only moderate wear of the pivot tip and are still in good operating condition.

It should be noted that a sharp blow on a table on which an instrument is standing may damage the instrument pivots by the sharp reaction of that blow to the instrument structure. Such sharp blows should be avoided.

All instruments are subjected in a greater or lesser degree to these hazards. Conventional panel instruments and portable instruments will withstand shocks of several times the value of gravity or, say 3 g, and vibration to a limited degree. Military applications, however, are such that much greater vibration may be applied to the instrument, and shocks of large magnitude are always possible in handling. Thus, military instruments have been designed particularly to withstand shocks and vibration.

Shock is always reduced where the instrument is mounted in a piece of apparatus because of the attenuation before the shock or vibration is transmitted to the instrument. The actual amount of vibration found in a plane is not unduly great nor are high shocks usually encountered. Extreme shocks are encountered when instruments are mounted, for example, in a tank and when the turret receives a direct hit. On shipboard, the Navy Department requirements for high shock are established primarily so that the equipment in question can be used after the ship has received a number of hits, but is still able to navigate.

Primarily, high shock and vibration damage the bearings of an instrument by flattening and distorting the pivots or by cracking the jewel bearings. Extremely high shocks may distort the moving system so that it will not swing clearly in its airgap.

Instruments designed to withstand high shock and vibration usually have a vibration isolating means incorporated in them, such as a rubber shock mount isolating the mechanism from the case or housing. Under heavy shock, the entire mechanism may move but the shock is mostly absorbed and considerable damage is prevented. In such instruments, the bearings are spring supported so that under heavy shock, which would cause the pivot to press into the jewel and deform, the spring-supported jewel will give way and retract to allow the pivot base to take the pressure against the face of the jewel screw.

Vibration may also affect the scale position. Scales for high vibration are frequently clamped between rubber absorbers. Springs for so-called ruggedized instruments tend to be somewhat shorter than good accuracy would dicatate so that they may be made relatively stiff and not vibrate in resonance with resulting deformation.

In general, all of the above factors are considered in the design of ruggedized instruments covered by MIL-M-10304A. Such instruments tend to be expensive. Furthermore, the features required to produce instruments to withstand large values of shock and vibration are not necessarily conducive to high accuracy and if the ruggedized instruments are not required, better results can be obtained with instruments of a more conventional type.

Moderate vibration is not much of a problem, but continuous and heavy vibration tends to wear the pivots. Vibration test cycles are specified in most military requirements and a great deal of work has been done to improve the bearing situation. Highly sensitive microammeters of low torque require sharp pivots to avoid frictional effects. Vibration will inevitably blunt these pivots, with consequent apparent sticking of the pointers. Highly sensitive instruments should, therefore, be isolated through shock absorbers from strong vibration.

Similarly, high shock may damage the bearings, although modern spring-supported jewels can withstand enormous shocks. Ruggedized instruments, mounted in a panel, for example, are specified to be tested by being struck by a hammer falling a definite distance. If heavy shocks are to be encountered, the ruggedized instruments will best fit the need. Acceleration is of secondary importance since the moving system is necessarily balanced. Acceleration of high value, as in projectiles, can be simulated by shock. On the other hand, indicating instruments rarely are used under accelera-

the condition of any considerable length of time which would cause damage.

Dust, Sand, Corrosion, and Fumes

Exposure to dust and sand is frequently a requirement. Sealed instruments appear to be the appropriate answer to this problem, although conventional panel instruments gasketed to a panel are frequently found satisfactory.

Corrosive atmospheres and fungus simply accelerate the effects of high humidity in corroding internal metal parts and destroying insulation. Where these conditions prevail, sealed instruments appear to be the best choice, with the widely used ruggedized instruments the type most commonly obtainable.

Radiation

The effects of sunshine, ultraviolet, or nuclear rays are quite limited. Sunshine and ultraviolet rays will fade some colors, particularly red; black ink appears to be immune to this difficulty. There has been no evidence of the effects of nuclear radiation provided the intensity is such that it is safe for an observer to approach the instrument within reading distance.

Summarizing the environmental conditions, one may say that conventional panel instruments may be used in any laboratory or ground station in the continental United States and, generally, in aircraft of conventional type. But military requirements, which may cover usage from the tropics to the arctic and shipment in any kind of vehicle, will probably make the ruggedized type of instrument necessary.

Overloads

In the application of instruments to electrical equipment, it should be noted that electrical overloads may be of several kinds. Instruments may fail mechanically, thermally, or by electrical breakdown.

Mechanical failure due to electrical overloads may occur by a sharp steep single pulse applied to a milliammeter which may slam the pointer and cause it to bend. A highly charged capacitor of large capacitance, apparently inert, can bend the pointer of a low-range milliammeter. Thus, in applying instruments to circuits where heavy filter capacitors are involved, some leakage path to discharge the capacitors is most desirable to prevent this type of electrical shock from damaging the instrument under abnormal conditions.

Similarly, a moderately heavy surge may even burn out the instrument spring or the heater of a thermoammeter without much motion of the pointer. Such surges would be much shorter than the time constant of the instrument and it is extremely embarrassing to have an instrument burn out before the pointer has moved materially. If the circuit arrangement is such that this may happen, a 1-mf capacitor across a d-c microammeter will frequently bypass any such surges in a d-c system.

Voltage surges occur rather seldom although it might be pointed out that the current surge in the previous instance may have such a steep wave front that the voltage developed between turns of the actuating coil may break down the insulation between those turns and effectively short circuit some of them. This will result in erroneous readings and is a hazard which should be prevented by consideration of this possibility and the use of the preventive capacitor shunt if the possibility of such surges exist.

Thermal overloads, essentially over periods of minutes, can occur particularly in the measurement of the average value of pulsed currents. It must be remembered that d-c instruments indicate on a basis of the average value of that current but are heated by the effective or rms value of that current. For example, a 100-amp pulse, 1 millisecond long, repeated ten times per second, has an average value of 1 amp and would so indicate on a 1-amp meter. But the rms or effective or heating value of this current is 10 amp and the 1-amp shunt in a conventional 1-amp instrument would be badly overheated by this continuous overload and might even melt out or fail in its soldered connections. On the other hand, for such applications where the problem is known and stated to the instrument manufacturer, over-capacity shunts can be furnished to withstand this thermal overload in a satisfactory manner.

In closing this discussion it must be pointed out that, not only should the best standard instrument be used if possible, but also that there is much the designer of electronic equipment can do to protect the instruments, circuitwise, from the hazards of overloading by surges. He should recognize that overloading may be inevitable in certain applications. When the problem is known—and

this is the equipment designer's domain—special instruments can be furnished.

INSTRUMENT DESIGN TRENDS

The trend is toward the use of smaller and more compact magnet systems which are magnetically better shielded. This is an important factor relating to the accuracy of instruments operated in strong magnetic fields, such as near a magnetron. The better shielding also confines the magnetic field to the instrument itself, thus avoiding harmful effects on nearby equipment, for example, a magnetic compass. Of course, instruments have been made more rugged in recent years, both as to electrical loads and mechanical shock and vibration. Better bearings and stronger materials are continually being introduced. Hermetic sealing is available in many instruments to eliminate the effects of moisture condensation due to rapid variations in ambient temperature and humidity.

SELECTION OF INSTRUMENTS

In the tabulation below, the usual types of instruments used for measuring the characteristics of the power in an electric circuit are listed. However, the listing is not exclusive and should not be considered as limiting. For example, the thermal ammeter is an excellent instrument for use at 60 cycles, but since its overload limit is only 100 percent, it will burn out on motor-starting currents where the iron vane instrument will take ten times normal load for several seconds and remain intact. Table 3-6 thus represents the best general selection.

In Table 3-6, it is assumed that for d-c measurements the average value is wanted,

Table 3-6—A Guide to the Selection of Measuring Instruments

Kind of power	Quantity to be measured				
	Voltage	Current	Power	Frequency	Phase
D-C continuous	Permanent magnet moving coil (PMMC)	PMMC	Electrodynamometer (Dyn)	--	--
Pulsating	PMMC (1,2,3)	PMMC (1,2,3)	Dyn	(4)	--
A-C 40-100 cps	Iron vane: Rect. type (1)	Iron vane	Dyn	Reed; other types	Power factor meter
101-2000 cps	Comp. iron vane: Rect. type (1)	Iron vane (5)	Dyn	Reed; other types	Power factor meter
2,000-20,000 cps	Rect. type (1, 5); Thermal type; Vacuum tube voltmeter (VTVM)	Thermal type	Thermal watt converter	Electronic type	Electronic type
20,000 cps to 1 Mc	Thermal type (5) VTVM	Thermal type	(6)	Electronic type	Electronic type
1 to 100 Mc	VTVM	Thermal type	(6)	Electronic type	Electronic type
100 Mc up	VTVM	(6)	(6)	Electronic type	Electronic type

Notes: (1) Reads average value
(2) Use electrodynamometer or iron vane type for rms value
(3) Thermal instruments will indicate rms value
(4) Use electronic gated pulse counter
(5) Preferably compensated for the frequency in use
(6) Rarely measured directly; determine by voltage across a known load

and for a-c measurements the rms value is wanted.

DO'S AND DON'T'S

In the application of panel instruments to electronic gear, attention is called to a brief list of important factors.

Do select ranges where normal operation will be in the upper half of the scale, around 3/4 scale for best results.

Do select meters appropriately adjusted for the panel being used, magnetic or nonmagnetic, or use shielded meters.

Do determine the effect of any meter used on the circuit. Run calculations accurately until it is clear the effect is negligible; alternatively, if the effect is definite, know what it is.

Do determine the particular military standard corresponding to the application, and select meters conforming to that standard. If the standard includes a list of ranges, make the range selection from that list.

Don't work so high on a meter scale that the pointer is frequently off scale; 120 volts full-scale is not high enough for line voltage, use a 150-volt range.

Don't work so low as a matter of safety that readings are below half scale; the meter can safely stand full-scale power continuously.

Don't mount an unshielded meter on a magnetic panel unless calibrated for same.

Don't hang gear on the meter terminals; they are for making connections, not for supporting equipment.

Don't use stiff connections to the meter terminals which may transfer mechanical vibration; if equipment is subjected to vibration, use flexible leads (stranded cable or thin strip) for heavy current connections. If the meter has threaded studs, use appropriate solder terminals.

Don't use a d-c meter for measuring pulsed dc unless the thermal capacity of the meter will handle the thermal loss produced; assume the maximum allowable thermal loss in watts in the meter as twice the full-scale loss under normal conditions of pure direct current.

Don't insist on many fine divisions on the meter scale; coarser divisions as described make for fewer reading errors with adequate accuracy.

Don't attempt to check an a-c panel meter on any frequency but that for which it was adjusted. Make certain the standard is known to be correct at that frequency. All a-c meters are adjusted for 60 cycles unless otherwise stated.

Don't pull up too tightly on the mounting screws; not only may they be stripped, they may also distort the instrument flange if the panel is warped.

Don't transport meters face up. By transporting them face down, the more important lower jewel bearing is preserved for normal face-up operation.

REFERENCES

1. Miller, John H, "Frequency Compensation of A-C Instruments," AIEE Transactions, Vol. 70, 1951.
2. Smith, U. L., "A Transducer Type Frequency Meter," AIEE Transactions, Vol. 74, Part I, 1955.

BIBLIOGRAPHY

Harris, F. K., "Electrical Measurements," John Wiley & Sons, Inc., New York, 1952.

Henney, Keith, Ed., "Radio Engineering Handbook," 4th Ed., McGraw-Hill Book Co., Inc., New York, 1951.

Knowlton, Archer E., Ed., "Standard Handbook for Electrical Engineers," 8th Ed., McGraw-Hill Book Co., Inc., New York, 1949.

Laws, Frank A., "Electrical Measurements," McGraw-Hill Book Co., Inc., New York, 1938.

Spencer, James, "Maintenance and Servicing of Electrical Instruments," 3rd Ed., Instruments Publishing Co., Inc., 1951.

Encyclopedia Britannica, 1957 Edition, "Instruments, Electrical Measuring."

Contents

CHAPTER 4 PRINTED WIRING BOARDS

Chapter 4

PRINTED WIRING BOARDS

Printed circuits are basically thin patterns of electrical conductors closely affixed to a supporting insulator sheet. Most often, printed circuits replace only wiring harness, but some circuit components may also be formed along with the printed conductors. Inductors may be formed by spiral patterns of the foil-like conductors, and small capacitors by opposed conducting areas fabricated on the two faces of the supporting dielectric, most feasibly for very high frequencies and ultra high frequencies. Specially designed conductors may also replace coaxial lines and some plumbing connections at microwave frequencies. Printed wiring is defined by EIA* as "a type of printed circuit intended primarily to provide point-to-point electrical connections or shielding."

By far the most commonly used printed wiring is a pattern (variously made) of 1- to 3-mil copper on a base of 1/16-inch plastic laminate, pierced with holes to receive the wire leads or lugs of standard circuit components and with larger holes to seat, fasten, and support the assemblage. Such an item may then replace a chassis or deck and is referred to as a printed wiring board, card, plate, or chassis.

Commercial specifications are mainly concerned with this kind of printed circuit. In general, standards and tests, unless specifically limited, are written broadly enough to include many other constructions of conductor patterns on nonconductors; for example, silver ink on glass wiring plates. Small ceramic-based printed circuits with printed elements and completely sealed are today regarded as unit assemblies in their own right and are subject to separate standardization.

It should be noted that for shipboard equipment the requirements of MIL-STD-376(Ships) must be followed, and that recommendations found in this chapter that do not agree with this specification are not permissible for shipboard equipment.

Compared to other components, the printed wiring board is quite new, and its standardization must be presently regarded in the status of "trends toward good practice." Rigid performance limits cannot yet be set down because their ultimate effects on durability are not sufficiently [illegible]. Also, in contrast to other passive components, printed wiring is almost never a stock item, for the most part being custom made for every application. Therefore, design practices, in addition to available standards, are appropriate determining means for quality control.

Knowledge of the applicable standards alone is insufficient to insure proper purchase and application of printed wiring. Unlike other components, the specification of printed wiring requires submission of a photographic pattern whose preparation presumes a knowledge of printed circuit designing.

Common Commercial Types

For etched circuits, the desired pattern is printed with acid-resisting ink by silk screen or offset press on metal-clad laminate, and the undesired areas of metal chemically etched away. Alternatively, a photosensitized colloid is coated on the clad stock, exposed under a photographic negative to a strong

*Electronic Industries Association, formerly Radio-Electronics-Television Manufacturers Association (RETMA)

light source, and the cladding washed free of coating in the unexposed areas to provide the resist pattern for etching. The several steps are illustrated in Fig. 4-1(A). The product comprises copper (rolled or electrolytic) or other metal conductors well adhered onto the surface of various pressed laminates or plastic sheet. Holes and mechanical fabrication usually follow but may precede etching. Repressing may be used to produce a flush circuit. Overplating etched laminate in selected areas is an important modification that may include through-hole plating over graphite, as shown in Fig. 4-1(C).

Plated circuits are begun by light overall metallization applied to adhesive coated plastic laminate. A resist is selectively applied as above, but reversed so that electroplating of copper or other metals fills the open areas, resist and metallization being subsequently stripped as shown in Fig. 4-1(B). The product resembles etched circuits in structure (usually having plated holes) but

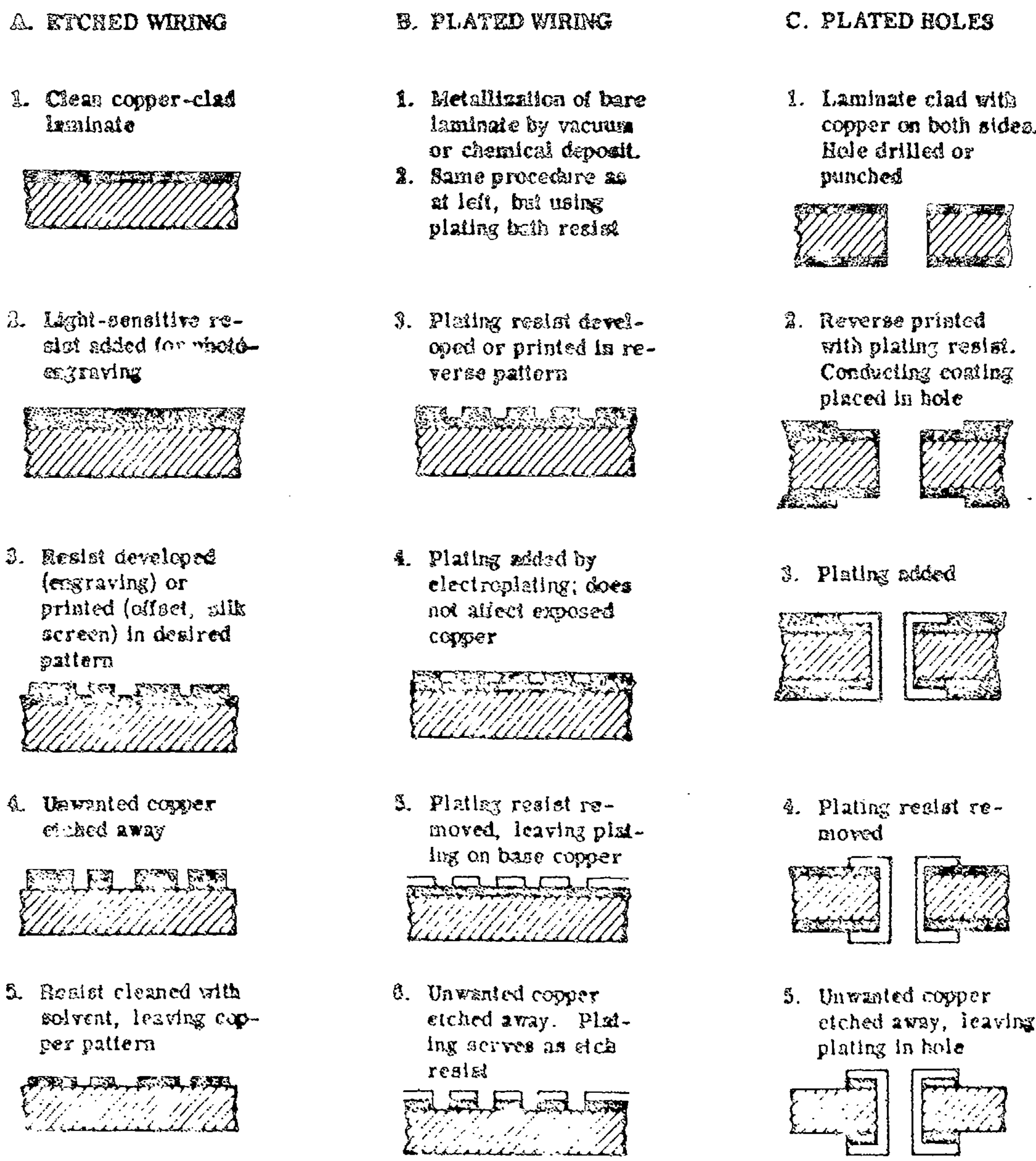


Fig. 4-1. Steps in process of producing etched wiring, plated wiring, and plated through holes.

differs somewhat in characteristics. Variations also yield flush-plated circuits.

Press-powder conductors begin as silver powder spread uniformly on a phenolic base (occasionally ceramic or other material). A heated die, bearing the desired pattern, effectively consolidates the silver into conductors by a brief high-temperature pressing.

Stamped, embossed, and blanked circuits account for a small proportion of printed wiring boards. In general, their manufacture utilizes diecutting or forming to separate the desired pattern from metal foil; the circuit being adhered by hot pressing to a laminate with adhesive or to a semicured stock. Conductance characteristics are, therefore, those of foil. All other properties depend on the nature of the insulating base.

General Utilization

The prime reason for using printed wiring is to provide for precise location of all components and the connections thereto, permitting the use of faster means of assembling. Identical fabrication of harness with quick changeover facility generally facilitates mass production. Secondary advantages of tidying up connective wiring often lead to size reduction, improved inspection and maintenance, as well as layout simplifications so that equipments definitely in low-volume production also benefit. Switches and other components can often be integrally designed. As an example, segments of a switch are shown in Fig. 4-2.

Long production runs may call for wiring produced by offset or silk screen applied resist if the slightly lower definition can be tolerated. Class B (130 C) and to some extent Class H (190 C) applications can be accommodated by utilizing better laminates and corrosion protected copper. For temperatures above 190 C, glass, ceramic, or glass-bonded mica bases are indicated.

PROPERTIES

As an index to the important characteristics, EIA has subcommittees devising printed wiring standards on (1) Adhesion and Solderability, (2) Definition and Register, (3) Mechanical Features, (4) Conductivity and Temperature Rise, (5) Arc and Flame Resistance, (6) Contamination and Corrosion, and (7) Insulation Resistance.

The Printed Conductor

The most common material is electrolytically formed copper foil (with some replacement recently by rolled foil of only slightly different character) of 99.5 percent purity. Before processing, this must be free of wrinkles, blisters, and inclusions of lead, with pinholes not to exceed 0.015 inch nor to occur more frequently than one per sq ft; otherwise,

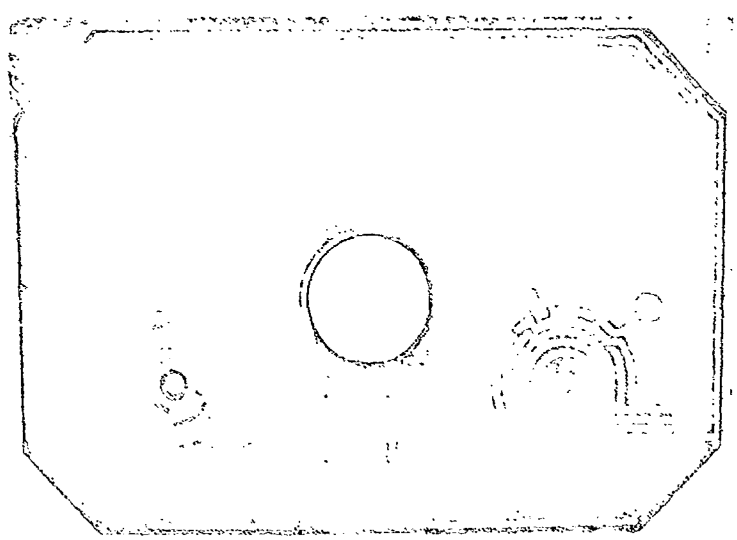


Fig. 4-2. Complex assembly can be designed as an integral part of the wiring pattern. This panel, for a tape recorder, has multipole switch segments incorporated at the lower left- and right-hand sections of the board. (Photocircuits Corp.)

conductors in the finished circuit may be loose or deficient in current-carrying capacity. Small physical irregularities in the surface cause misprinting in the production process and may result in gross defects.

Foil thicknesses are:

Nominal 1 ounce—0.0014 inch plus 0.0004 inch minus 0.0002 inch

Nominal 2 ounce—0.0028 inch plus 0.0007 inch minus 0.0003 inch

Bond of the Conductor

The conductive film must be resistant to delamination during soldering or high-temperature operation as well as to blister deformation in processing. Procedures for three parameters are provided in EIA Standards Proposal 484. Minimum blistering resistance is a 10-second float of the specified test pattern (Fig. 4-3(A)) in 230 C solder, followed by visual inspection. The adhesion of terminal areas about holes is checked by measuring the force required to detach a No. 18 AWG sample wire previously dip soldered in place. The general adhesion of conductors to the base stock is determined by measuring the force required to peel a 1/8-inch wide conductor, pulled at right angle to the base; the result in pounds is multiplied by eight and stated in pounds per inch width. The latter two tests can also be utilized after simulated dip soldering, oven baking, or other anticipated conditions to be encountered in assembling or use. Minimum values for various materials, suggested by suppliers and by other agencies (whose procedures may vary slightly), are summarized in Table 4-1, in which bond strengths are given "as received" from the manufacturer. Some users require as high as 8 pounds peel strength, and this after solder dipping. However, this does not guarantee better boards; some laminates, initially poor in bond, are improved after such heat treatment, while others deteriorate. (1)

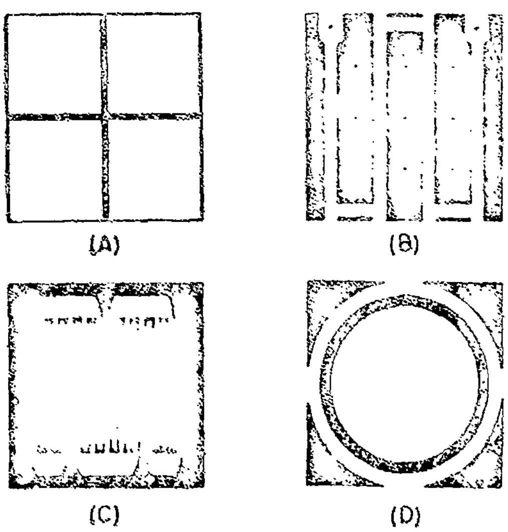


Fig. 4-3. Tentative EIA test patterns: (A) Blistering. (B) Conductivity, temperature rise, bond strength and solderability. (C) Insulation resistance. (D) Surface and volume resistivity, dielectric constant and dissipation factor.

Delaminating assumes importance not only at soldering but also during baking-on of etching resists in processing, so that circuits and clad-laminates need specification for oven endurance. Performance minimums are given in Table 4-1. Special environmental endurance may also suggest additional oven requirements appropriately elevated for accelerated tests, which are comparable to Insulation Class A, B, or H levels or include temperature or humidity cycling. Notably little account has been taken in current specifications of possible bond impairment during unsoldering and repair. Hannahs has reported suggestively that unsoldering takes longer than soldering, reaches well over 300 C, and that free-standing tip temperatures even of small pencil irons reach 350 C. (1)

It should be noted that the properties measured by "peeling" conductor are different from those evaluated by straight "pull" and that values from the two types of tests are not convertible. No minimum has yet been set for the lead pull-out test above, but a 5-pound minimum might be considered from ordinary wire-to-lug soldering practice; 15 pounds is a typical test value.

Mil-P-13949(SigC) requires that the initial bond strength between the metal foil and the base material at room temperature be not less than 5 pounds when a 1-inch strip in the middle of a specimen 3 by 3 inches is pulled perpendicular to the panel surface at a rate of 2 inches per minute.

Peel requirements on flexibly based circuits are also not strictly correlatable with rigid base items because convenience dictates test separation of conductor and insulation at a 180-degree angle. The adhesion of fired silver circuits or others of consolidated metal is probably better determined by scratch or abrasion testing, although figures of 2000 psi have been given for silver on

Table 4-1—Delamination Strengths and Thermal Endurance

Circuit base	Max continuous operating temp (deg C)†	Basic peel strength (lb/in. width)	Soldering endurance, time and temp (sec & deg C)	Time in oven (min)
Thermosetting, all	—	5 min* (C)	5 sec at 260 C (C)	60 at 140 C (C)
XXXP (1 oz Cu)	121 (A)	5 av (B) 4 min (B)	10 sec at 232 C (B)	30 at 130 C (B)
XXXP (2 oz Cu)	121 (A)	6 av (B) 5 min (B)	10 sec at 232 C (B)	30 at 130 C (B)
Nylon-phenolic	74 (A)	4 to 7 (A)	—	—
Glass-melamine G-5	135 (A)	5 to 8 (A)	—	—
Glass-polyester GP 9109	120 (A)	2 to 6 (A)	—	—
Glass-silicone G-7	120 (A)	3 to 7 (A)	—	—
Glass-epoxy G-10 (1 oz Cu)	150 (A) 175 (A)	6 av (B) 5 min (B)	15 sec at 232 C (B)	30 at 130 C (B)
Glass-epoxy G-10 (2 oz Cu)	175 (A)	7 av (B) 5 av (B)	15 sec at 232 C (B)	30 at 130 C (B)
Kel-F	180 (A)	6 min (A)	10 sec at 240 C (A)	—
Glass-Teflon	200 (A)	6 to 9 (A)	260 C. (A)	—
Glass-bonded mica (fired)*	343 (A)	—	—	—
Steatite (fired)	—	—	245 C (A)	—
Standardizing Agency: (A) Suppliers, (B) NEMA—tentative 1956, (C) Signal Corps				

*After temperature cycling -55 to 85 C

†The meaning of maximum continuous operating temperature has not been well standardized by the industry. The data given in Column 1, supplied by various manufacturers of clad laminates, is subject to variation between suppliers. Underwriters' Laboratories standards for all phenolic-based laminates sets a maximum continuous operating temperature of 105 C.

steatite and 600 psi for press powder on phenolic.

Definition and Registry

Ragged and ill-defined patterns obviously affect the spacing of conductors and may result in leakage or arc. Registry of conductors from face-to-face of the card and with respect to the location specified may also affect electronic function, but misregistry of pattern to punched holes is most likely to result in faulty soldered joints. EIA Standards Proposal No. 508 treats specific definition as the maximum crest-to-trough roughness measured within any distance of 1 inch along a conductor, as shown in Fig. 4-4. In general, photoetched conductors may be expected to have finer definition than silk-screen etched conductors. Commercial allowable front-to-back misregistry for plain etched circuits is 0.015 to 0.025 inch and with plated holes 0.020 to 0.025 inch, the range dependent largely on price. Definition and registry quality, first established in a master drawing, must be retained in photograph negatives and the accurate transfer thereto.

Conductivity and Temperature Rise

A printed circuit will carry several times the current of an equivalent size wire for the same temperature rise because of diffusion of heat into the attached base. (2) Thermal difficulties are generally the result of hot environment or hot spots near tubes. The

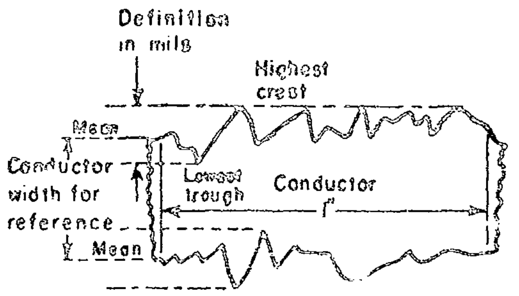


Fig. 4-4. Conductor definition and registry measurement of printed wiring conductor. Scale is exaggerated for illustration.

conductivity of electrolytic copper foil is recently reported at 1.80 10 ohm-cm at 35 C and the temperature coefficient equals 0.00385. Silk-screened conductors fired on ceramic are of the order of 0.01 ohm per square,* with excellent dissipation, and approximately 0.05 ohm per square screened on plastic.

Filament leads and other heavy current carriers in a design should be checked for possible overheating, preferably by fine-wire thermocouples (No. 40) cemented directly to the conductor. Published design data for current capacity is in considerable discrepancy due to nonagreement on method, as Fig. 4-5 will show. These variations are illustrative of thermal differences that also occur in practical application, namely, local ambient temperature, proximity of conductors, area of board, configuration of pattern, and vertical vs. horizontal mounting. The two most conservative of the curves shown are representative of temperature rise in a typically hot (60 C) enclosure. (1) The type of adhesive bond used may appreciably modify temperature rise by affecting thermal conductivities, and adverse effects of solder dipping has also been suspected.

Current capacity is appreciably improved by going from 1/16- to 1/8-inch XXX phenolics or leaving the copper on the reverse side. Hoynes has shown that protective coatings reduce current-carrying capacity by 15 to 20 percent. (3) In general, current capacity is directly related to the thermal conductance of the base materials. The thermal ceiling on plastics should always be treated conservatively for trouble-free life, and material with greater thermal conductance used when in doubt.

Where a printed deck replaces a metal chassis, heat transfer from mounted components must be examined. Power-output tubes and resistors may need thermal ground straps or heat-diffusing plates to avoid local hot spots.

Metal-Clad Laminates

The physical and electrical characteristics of printed wiring are heavily dependent on the properties of the insulating base stock, which most commonly is a high-pressure laminate of paper or glass cloth impregnated with phenolic and other resins as shown in Tables 4-1 and 4-2. Varieties of NEMA Grade XXXP, a paper-base phenolic, are widely used because of low cost combined with generally excellent electrical and physical properties and ease of fabrication.

Manufacturers have improved the properties of clad laminates over those of NEMA minimum standards so that generally better values are obtainable in moisture absorption, insulation resistance, soldering endurance, punching properties, dielectric strength, and general physical properties. XXXP is not good in arc tracking, such as results from the wiping action of brushes on printed commutators. No laminate is superior in all proper-

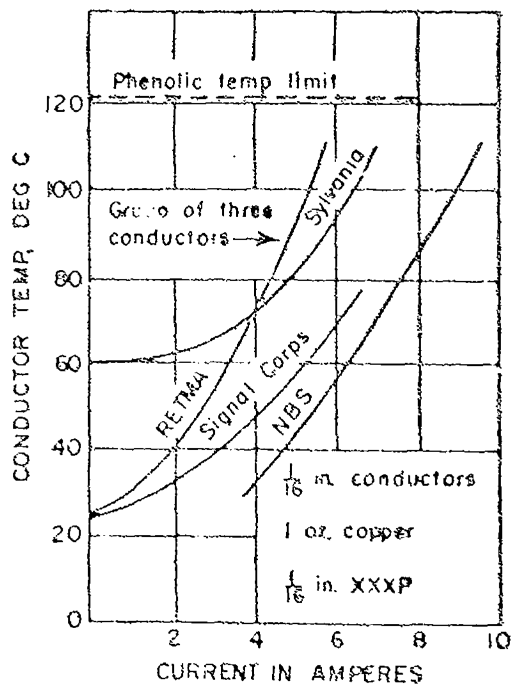


Fig. 4-5. Current-carrying capacity of etched circuits.

* A dimensionless constant.

Table 4-2—Clad Laminates, Mechanical and Electrical Properties*

	Water absorption (% 24 hr)	Insulation resistance (megohms)†	Dissipation factor (1 Mc)	Dielectric constant (1 Mc)	Arc resistance	Flexural strength (psi × 1000)	Punching quality
XXP	1.6	500	0.037	4.6	poor	17	excellent
XXXP	0.7	7×10^4	0.028	4.0	poor	23	excellent
XXXP (cold punch)	0.6	5×10^4	0.035	4.2	poor	[illegible]	excellent
Linen-phenolic LE	1.95	30	0.055	5.8	poor	15	excellent
Nylon-phenolic N-1	0.3	5×10^4	0.03	3.3	poor	13	excellent
Polyester-glass mat GP-9100	0.2	100	0.015	4.3	good	25	good
Glass-epoxy G-10	0.16	1×10^5	0.025	4.0	good	60	fair
Glass-melamine G-5	0.6	100	0.020	6.8	good	55	fair
Glass-silicone G-7	0.20	2,500	0.015	3.9	good	40	fair
Glass-Teflon	0.3	5×10^4	0.001	3.3	v.g.	13	good

* Typical commercial values
† After 96 hr at 35 C and 90 RH

ties; electrically, cold-punching XXXP is not the best obtainable. Conversely, clad XXXP may be quite adequate to some applications. Epoxys and polyesters can also be considered if cold punching is required. Where otherwise permissible, linen and nylon stocks will permit greater yield without cracking in intricate punching or staking. Cloth grades also permit a little more forming than paper laminates, but intricate forming requires a clad post-forming stock. Phenolics resist oils and solvents well but are somewhat susceptible to moisture.

Synthetic fiber cloth stocks are still primarily nylon; nylon with phenolic being outstanding for insulation resistance under humid conditions and having excellent mechanical properties. Its limitation is in temperature (Table 4-1).

Melamine-glass cloth clad laminates are appropriately employed in commutative and switching devices where low arc tracking and a higher temperature endurance are called for, but the glass fiber produces greater tool wear. Its moisture absorption is intermediate (see Table 4-2).

Epoxy-glass cloth clad material is largely superior to the phenolics in both electrical and mechanical properties. Machining is slightly more difficult than for paper-phenolic. The material fits well in applications calling for good insulation resistance, low moisture absorption, heat resistance, low loss, excellent mechanical strength, and punching.

Silicon-glass cloth clads are made with either staple-fibre G-6 or continuous-filament G-7 material. Very low dielectric loss, together with generally superior electrical and mechanical properties, recommend the material where inductors of high Q or stability are involved. Heat resistance is high, but limited by the epoxy conventionally used as a bonding agent. To some extent this also determines surface characteristics.

The polyester glass-mat laminates lie midway between the phenolics and epoxys. Moisture absorption and loss as well as punchability are generally superior to the phenolics. They are used where the better mechanical properties of epoxys are not required.

Circuits made on fluorinated hydrocarbon clads (Tables 4-1 and 4-2) are excellent in all electrical properties and stay that way in high temperature and high humidity. They are indicated for microwave circuits and for high-temperature environments.

Mechanical and Thermal Properties

A tendency to treat printed circuits on laminate bases as though they are steel

plates has led to trouble. Large printed circuits fastened rigidly at four corners may buckle or break out. Laminates are simply not that stable. Nominally, XXXP has twice the thermal expansion of steel, and there is a growing inclination to recognize that expansion on thermal cycling is not entirely reversible (interpretable as a "hysteresis"). In many laminates, size change after hot punching may seriously affect the location of holes. Warping and dimensional change are, of course, also a product of moisture absorption. (See Table 4-2).

Maximum dimensional stability, when demanded for frequency determining elements, is obtainable from inductors printed on glass or ceramics.

Warp and twist are traceable primarily to the fundamentally different properties of metal conductors and insulating base. Consequently, single-side circuits are far more susceptible and large conductor areas, if unopposed by cladding on the reverse, should be designed as a grid. The overall area of printed cards should be limited because automatic assembling machinery generally handles panels of modest size only (see Table 4-8). Dimensions over 8 inches may call for 1/8-inch laminates. NEMA Standard LP-1 limits warp and twist in clad sheets. Individual cards or decks can be checked by ASTM-D709-52T; flexural strength and flexibility is determined by ASTM-D790. Commercially acceptable limits for warp are given in Table 4-3.

Machine handling of circuits, as well as their fit in sockets, is interfered with by warp and twist together. This combined effect is the subject of current standardization efforts by EIA Automation Subcommittees.

The design of ceramic based printed circuits is very specialized and should be done in consultation with a ceramic or glass technologist.

Table 4-3—Commercial Limits on Warp

Base material thickness (in.)	Warp (in./in. of length)
Single-side pattern	
1/16	0.025
3/32	0.020
1/8	0.012
1/4	0.006
Double-side pattern	
All thicknesses	0.005

Conductors vs. Insulation Resistance, Coatings

In the laboratory, etched lines in 1-ounce copper can be made as close together as 0.005 inch. However, quite a few practical considerations set the practical minimum for line spacing in the range of 1/8 inch down to about 1/32 inch. Normal variations in the photomechanical processes make both lines and spaces less than 0.025 inch troublesome in production, and 1/32 inch is a practical minimum from this standpoint. Solder bridging is not the prime factor in determining line spacing, and with well controlled soldering 1/32-inch spacings can be used, but 1/16-inch spacings are advised to avoid the usual nonoptimized conditions in factory operation. Lines spaced 1/16 inch on most copper clads have a capacitance of about 1 mmf per inch. This increases about 20 percent when the spacing is reduced to 1/32 inch. Unwanted capacitative coupling effects can be judged accordingly. Peak voltages should also be taken into account and derating for altitude as in other equipment.

Signal Corps recommendations as of July 1957 are as follows for rated voltages for various spacings of printed conductors for use in equipment operated at or near sea level and having a maximum available input power of 50 watts:

Conductor spacings for printed wiring patterns protected with an appropriate conformal coating on hermetically sealed assemblies

Voltages (DC or Peak AC)	Conductor Spacings (in., preferred)
300 to 500	0.060, 0.125
100 to 300	0.030, 0.060
Below 100	0.020, 0.030

Conductor spacings for unprotected portions of printed wiring patterns

Voltages (DC or Peak AC)	Conductor Spacings (in., min)
300 to 500	0.300
100 to 300	0.125
Below 100	0.060

For protected printed wiring, the preferred spacings given above shall be equalled or exceeded whenever space permits. For applications where secondary short circuit protection in the form of fuses, circuit breakers, and so forth, are provided; and where the normal operating power is greater than 50 watts but does not exceed 2000 watts, the

spacings given above shall be doubled. Special attention should be given to the selection of a base material when the input power exceeds 50 watts. Electrical spacings shall be adequately increased for critical applications such as equipment operated at high altitudes.

The effect of moisture on printed circuits resembles that of its effect on the base laminates alone except that when an adhesive is present, an adhesive layer is left exposed after etching. Therefore, design data utilized should be for etched clad laminates, as in Tables 4-2 and 4-4, not for ordinary unclad laminates. The effect of humidity and temperature on clad laminates, not subjected to etching, is shown in Fig. 4-6. This data is a compilation from several extensive testing programs; the poorer insulation endurance of epoxy at 70 C may be due to copper corrosion products. Insulation resistance measurement of any given grade of laminate is extremely difficult to reproduce; better agreement is securable on specific equipment or designs. Experience seems to indicate that 90 percent humidity is more easily reproduced than is 93 RH or higher. Recommended test is by the pattern of Fig. 4-3 with a fixed processing procedure.

The insulation resistance over the area of a single piece of printed wiring varies widely and if plotted, looks like a topographic map of very mountainous terrain. Martin, and others, have shown that the extensive chemical processing of cleaning, etching, and plating circuits very widely influences the susceptibility of the bond layer to insulation change by moisture, particularly sludge deposits from spent etching baths and "noncorrosive" flux residues. (4)

Coating Density

Accumulations of dust and finger prints are moisture traps and lead to conductive corrosion products so that protection of printed wiring by coating and even potting is advised. Outside of the generalization that coatings must be relatively heavy (5 mils) to reduce moisture permeability adequately, there is no

Table 4-4—Distributed Capacitance of Etched Conductors Mmf per Square Inch

Spacing (in.)	XXXP	XXP	Melamine-glass	Teflon
1/32	1.33	0.88	1.26	0.39
1/16	0.85	0.73	1.10	0.36
1/8	0.72	0.60	0.90	0.33

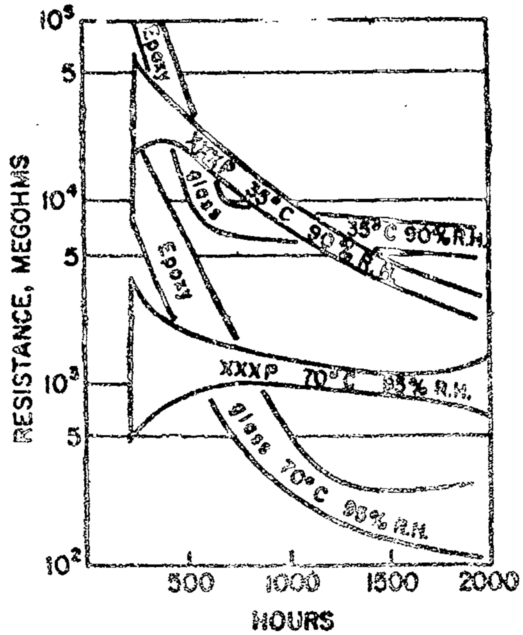


Fig. 4-6. Curves showing insulation resistance of clad laminates.

agreement on the comparative effectiveness of various coating types, except microcrystalline waxes, which generally are quite good. Commercial practice sometimes allows rosin flux to remain as protection, but the advisability of this depends on control of the amount of "fluxed-off" impurities contained in the coating.

Coatings are also needed to reduce metal migration and to restrict arc, which in phenolics is cumulative, due to carbonizing. Leakage over surfaces between conductors generally begins at 220 volts per inch (1/64-inch spacing) and arc-over occurs at 2000 to 3000 volts per inch. Residues from moisture and corrosion greatly reduce this. Only heavy coatings, free of pinholes, or complete potting, preserve initial arc-resistance qualities.

Coatings, however, do not present an open and shut case. There are advantages and disadvantages. If the board is uncoated, there is always the possibility of the degradation of the electrical characteristics of the board when exposed to contamination plus the necessity for optimum conductor spacing. When the board is coated, reduction of the deleterious effect of moisture is secured.

Bureau of Ships has determined: (1) that there is a 15 to 20 percent reduction in

current-carrying capacity of the conductors, (2) that the surface resistivity values experience considerable variation over and above that recorded for uncoated samples, and (3) that no coating entirely prevents the formation of corrosion. In addition, the repairability of a coated printed board on shipboard is questioned. If, as a result of heat from a soldering iron (or a porous original coating), exposed areas remain, there is the probability that moisture will enter the exposed areas and by capillary action become entrapped in unexposed areas. This is a worse situation than prevails on an uncoated board from which this moisture can evaporate as the temperature is cycled.

For these reasons, Bureau of Ships, in keeping with its policy of requiring completely repairable assemblies, prefers uncoated printing boards.

For other services, printed wiring assemblies may be completely potted or encapsulated. No encapsulations or potting compounds have been specifically standardized for printed wiring; those in general use for other electronic assemblies are acceptable.

Dielectric Characteristics; Capacitors, Inductors

Dielectric constants of several clad laminates are given in Table 4-2. With an average dielectric constant of 5, 1/16-inch clads yield about 20 mmf capacitance per sq in.; through 0.005-inch flexible glass-phenolics, capacitances of about 200 mmf per sq in. are obtainable. Capacitors of the comb type, Fig. 4-3 (C), are difficult to stabilize due to fringe capacitance, except on the very lowest loss materials. Capacitor areas placed at the center of inductors in traps and filters may replace an eyelet by capacitative feed through.

The variation of capacitance with frequency is calculable from the typical graph of dielectric constant in Fig. 4-7.

The distributed losses in straight lines is indicated in Table 4-4 and may require separating high-frequency conductors considerably or introducing intermediate grounded lines for shielding. Only the lowest loss materials are practical for microwave conductors.

Inclusion of inductors in printed wiring, which is practical at ultra high frequencies and the higher portions of the vhf range,

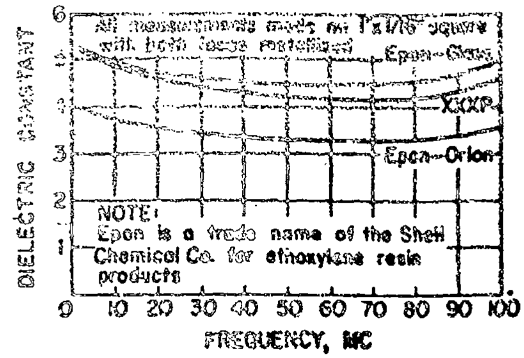


Fig. 4-7. Curve showing dielectric constant vs. frequency for several base materials. (The Mica Corp.)

may substantially reduce assembly cost. Typical design values are shown in Table 4-5. Line widths greater than 0.010 inch are more consistently reproducible. Dissipation losses are shown in Table 4-2, and the variation of power factor vs. frequency is shown in Fig. 4-8. The Q obtainable with inductors of the 1- to 5-microhenry size may be as high as 50 to 200. However, inductors for broadcast frequencies have prohibitively low Q on XXXP due to losses. The spacing between lines in spiral inductors has a very large effect on Q.

A nomograph for spiral inductor design is shown in Fig. 4-9 to which the following directions apply:

1. Assume a winding pitch of 30 mils (one line width plus one space) and a ratio of average radius to winding of 2.
2. Draw a line through the pitch and A/C ratio values intersecting the reflect axis.
3. Draw a second line from this point on the reflect axis to the desired inductance value.
4. Read the number of turns required at the point of intersection with the turns scale.

The following formulas derived from the spiral coil diagram are helpful, if other variables are fixed:

$$C^{*} = P\ (\text{pitch}) \times N\ (\text{turns})$$

$$C^{*} = \frac{\text{Outside diameter} - \text{inside diameter}}{2}$$

$$A^{\dagger} = \frac{\text{Outside diameter} + \text{inside diameter}}{4}$$

---

* C is the winding depth.
† A is the average radius.

Table 4-3—Inductance of Etched Spirals

Microhenries	O.D.-I.D. (in.)	Line widths, spaces (in.)
0.75	7/8 - 3/8	0.020
1.75	3/4 - 3/8	0.018
3.50	1-1/4 - 1/2	0.015

For silver ceramic circuits at 1 Mc the dielectric constant is about 5.58 and the loss factor 0.0042. With plating, 2-microhenry coils will attain a Q of 125 at 100 Mc.

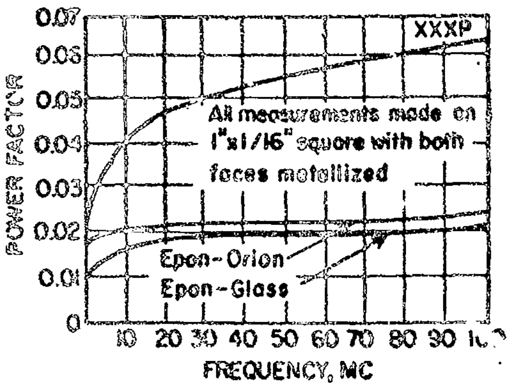


Fig. 4-8. Curve showing power factor vs. frequency. (The Mica Corp.)

APPLICATION

Assembly of Components; Retention, Soldered Joints

Most small circuit components are now available in types having leads or lugs for inserting into holes in printed wiring and dip soldering; this includes resistors, paper electrolytic and ceramic capacitors, diodes, transistors, potentiometers, R-C unit assemblies, pulse transformers, rectifiers, tube sockets, and some others, as shown in Fig. 4-10. In a few cases, some progress has been made in standardizing pin spacing and diameters; see Table 4-6. There is also a basic standard (EIA RS-188) toward getting all terminations on a "grid module" of multiples of 0.025 inch. Some leads or lugs

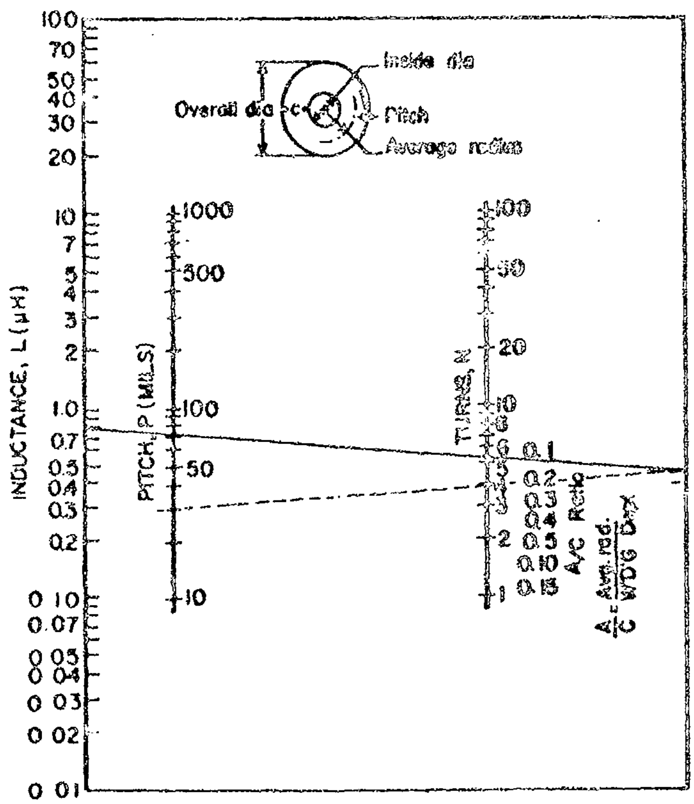


Fig. 4-9. Nomograph for printed circuit inductor design.

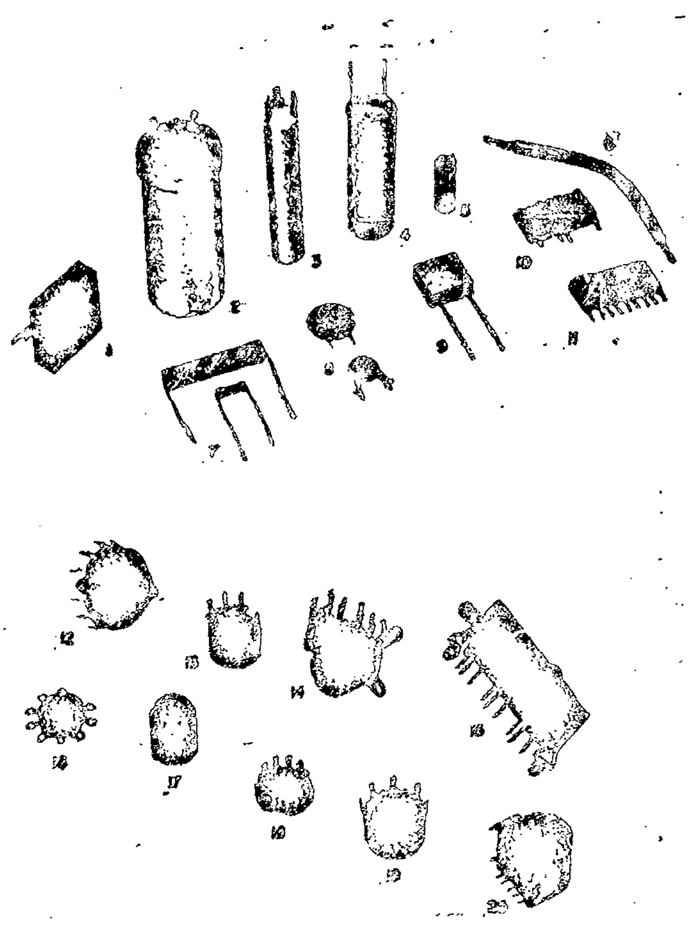


Fig. 4-10. Components developed for use in printed wiring boards. 1. Selenium rectifier with snap-in terminals. 2. Electrolytic filter capacitor with lock-in tabs and connections keyed to wiring board holes. 3. Power resistor with prongs arranged to prevent improper connection. 4, 8, and 9. Foil and ceramic capacitors. 5. Small tubular capacitor. 6. Flexible power resistor. 7. Miniature power resistors. 10 and 11. Integral units containing resistors and capacitors internally connected. 12. Multiple rotary switch. 13. Screwdriver-operated variable resistor. 14 and 15. Variable-resistor controls. 16 through 20. Various types of tube sockets.

are stiff and short, to be used uncut; others are flexible and require cutting and forming as used. A few components can be had on tape in reels. Methods of assembling common components are found in Table 4-7.

Generally, all conventional components are mounted on the side of the printed circuit board opposite the pattern so that they are not immersed in the solder during the dipping operation. In the case of two-sided circuits, the components are mounted on the side opposite the one to be dipped. If components are to be mounted on the dip side, they must be assembled after dipping and soldered with a hand iron.

Holes to receive components must be within a few thousandths of an inch to provide capillary rise or proper fillet in soldering, or faulty joints will result. Compromise here is difficult: for 0.032-inch leads, 0.050-inch holes make automatic insertion more certain, but 0.042-inch holes give stronger soldered

Table 4-6—Typical Automatic... Terminals

Component	Terminals
Electrolytic capacitor, 1-3/8 in. O.D. electrolytics	0.030 in. wide, 0.265-in. projection on 0.328-in. radius circle
1-in. O.D. electrolytics	0.040 in. wide, 0.171-in. projection
Electrolytic capacitor, 7-pin tube sockets	Fit 0.065-in. holes, project 1/8 in. on 0.740-in. diameter circle
9-pin tube sockets	Fit 0.065-in. holes, project 1/8 in. on 0.835-in. diameter circle
Ceramic disk capacitors	Lugs 0.063 in. × 0.010 in. or No. 20 wire spaced 0.250 in. or 0.375 in.

joints. Spring clips inserted in holes or clinched to leads are occasionally used to improve this fit and thus soldered joint strength. With regard to eyelets, however, some engineers are opposed to their use, finding more impairment in the board and conductor side of the joint than improvement between lead and eyelet. Simple well-filleted joints are regarded as best by many.

Since every part within shipboard equipment is subject to replacement, printed wiring board construction techniques must allow for repetitive soldering and unsoldering operations without degradation of the foil-to-plastic bond. Therefore, eyelets are required for shipboard equipment.

Although flared eyelets may give a more reliable electrical connection than rolled eyelets, field experience generally indicates that eyelets should not be depended upon for electrical connection. Therefore, MIL-STD-275 requires that leads be clinched directly to the foil, thus eliminating the eyelet from the electrical path. Several mounting methods are shown in Fig. 4-11.

Mechanical retention of small components is by leads alone; the strongest joints (22 to 30 pounds) occur when the leads extending through holes are clinched over, but no agreement has been reached as to the necessity of clinching, such construction being with total reliance on the wedging retention of solder in the hole, reported at 15 to 30 pounds.

It is equally important to mount the component to prevent leads pulling or pushing the conductor loose. The mountings of Fig. 4-11 labeled "swaged" and "bent" have better convective heat transfer. To pass vibration requirements, lead lengths should be a minimum and lead bend radii large; on any but a very small card it will almost certainly be necessary to "shake down" the final design. Generally, components of over 1/2 ounce should be tied to the board; and in the range of 100 g (acceleration) to 400 g, smaller components should be properly tied. Boards plugged in edge connectors, Fig. 4-12, need special attention by clamping at their upper end.

Some experience indicates that epoxy resin can be used to hold down small components to withstand 20,000 g shock and 20 g vibration, 0 through 2000 cps.

Data for quality control of soldered joints in suspect equipment can generally be obtained by two or more 48-hour cycles at 71 C, the second at 95 percent RH. (6) Temperatures as low as -65 C do not directly affect boards unless frosting occurs, but weak solder may give way.

Soldering. Reliability of the end equipment is heavily dependent on soldering conditions. Bath temperatures ordinarily used to secure finely flowed joints between metals cannot be employed with laminate-based wiring that is likely to suffer from blistering and impaired bond strength at a value of plus or minus 20 degrees of 232 C. This is not far above the liquidus (180 C) even of the near-eutectic solders usually specified for clads. Solder 60-40 with a liquidus of 190 C can be used, but the range of fluidity is further compromised. Pot temperatures are frequently lowered by inserted assemblies to the slush point. Consequently, large baths with closely regulated temperatures are advised, and the surface should be kept scrupulously clear of dross.

It is not possible to discuss here all the parameters of mechanized soldering of which there are several types. All soldering is compromised by conditions, and since mechanized soldering involves the simultaneous

Table 4-7—Method of Assembly of Components

Component type	Available in modified form for dip soldering	Suggested method of installation
Resistors—1/4- to 2-watt, insulated, carbon	No—but are available with preformed leads	Bend leads at right angles no closer than 1/8 inch to resistor body and push through holes in circuit board. Bend over or crimp on bottom.
Resistors—5- to 20-watt, wire-wound	No	Bolt mounting strap to board and insert leads through holes provided in circuit.
Capacitors—ceramic disk, tubular	No	Bend lea[illegible] and insert in holes provided in board.
Capacitors—electrolytic, tubular	No	Bolt mounting strap to board. Insert leads in holes provided.
Capacitors—electrolytic, metal	Yes	*Tabs inserted in holes and bent, or in slots and twisted.
Capacitors—tuning	Yes	*Terminals extend through slots in board.
Transformers—i-f	Yes	*Terminals snap into slots in board.
Transformers—r-f	No	Insert bent leads through holes in board which will serve as support.
Transformers—audio and power	No	Suggest heavy transformers not be mechanically mounted on plastic boards.
Tube sockets—molded 7-pin, 9-pin, octal	Yes	*Snap in single hole. Available with or without keyway. Shields and holders also available.
Tube sockets—subminiature	No	Mount standard sockets, pins through board. Advisable to wire tube directly to pattern and eliminate socket.
Volume and tone controls	Yes	*Tabs inserted into holes in board. Available with or without right angle mounting provisions.
Selenium rectifiers	Yes	*Tabs snap into slots in board.
Plugs and receptacles	Yes	*Printed circuit pattern of parallel lines brought to the edge of the tongue on the board plug into special receptacles made for this purpose.

Table 4-7—Method of Assembly of Components (cont.)

Component type	Available in modified form for dip soldering	Suggested method of installation
Coils—wire-wound, nonvariable, tubular	No	Mount on board same as carbon resistors.
Coils—toroids	No	Mount on board in conventional manner, then attach leads through holes in board to pattern on opposite side.
Coils—tuned	No	Mount to board in conventional manner. Insert wire leads through holes to meet pattern.
Coupling units—printed on ceramic	Yes	*Have tabs along one edge to fit into holes in board meeting pattern on opposite side.
Eyelets, turret lugs, stamped lugs, pilot, lamp hardware	No	Usually mounted to board in conventional manner.

* Check specific component manufacturers for details.

establishment of a large number of soldered joints, it generally resolves into a struggle to provide optimum soldering circumstances. To have some working range below the ceiling set by the endurance of printed wiring, it is advisable to use near-eutectic alloy and to control contamination entering from metals dissolved from component leads, and the like, which might raise the melting range. Optimum conditions are preserved by use of clean oxide-free leads and by having wiring boards pretinned or plated. Normally, dip soldering can be performed satisfactorily in 2 to 3 seconds, but any departure from the most favorable conditions increases the required time. Very heavy component lugs may also require longer dip times and possibly higher bath temperatures.

Wiring boards, if not freshly cleaned, require protection either in the form of electroplating (solder plating), hot tinning, or use of a noninterfering "water dip" lacquer. The protecting metal should not be one that will impair the solder in the pot as it accumulates.

The only established noncorrosive flux is W-W rosin in alcohol, but its fluxing action is too mild if the parts are badly tarnished, resulting in defective joints. Activated fluxes yield consistently better joints, but their activating agent, which is removed by the heat under optimum conditions is corrosive and conductive. Flux removal, with solvents safe to clad laminates, is most advised.

Extensive references on the general art of soldering in electronic equipment can be found in the proceedings of two EIA symposia. (6, 7)

Selective areas may be soldered by the use of masking tapes; wax flux resists have also been suggested by Gamson. (8)

DESIGN REQUIREMENTS AND PROCEDURES

In designing printed circuits, the choice of base material is the first consideration. This is dependent upon valuation of all the mechanical and electrical properties against the specific environment, endurance, and cost limits set by the end equipment.

The size and shape of the board basically depend upon the number of circuit components and the mounting space available in the equipment. Consideration must be given to warp, strength parameters, shock, vibration, and temperature cycles that may affect or limit dimensions. Designing for mechanical strength in the laminate is a major factor in producing longlived equipment. It is often

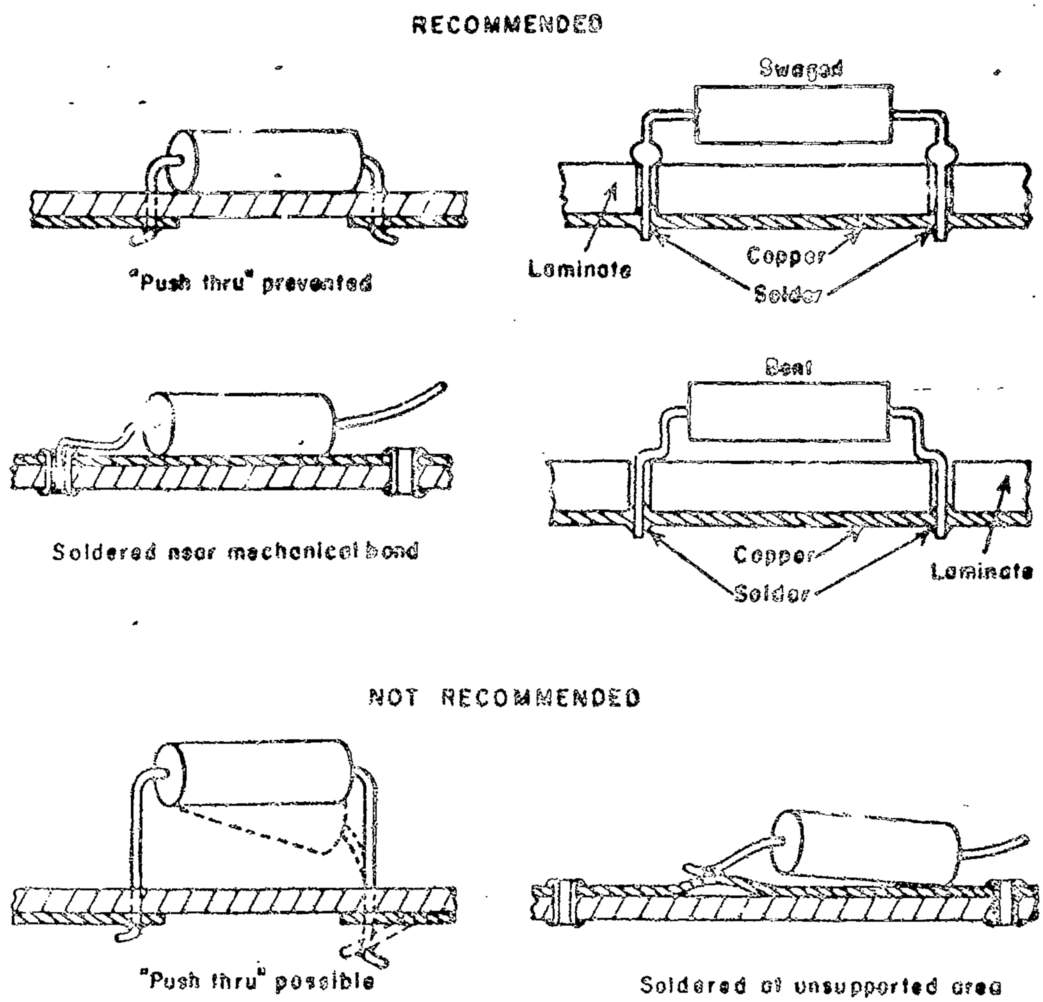


Fig. 4-11. Methods of mounting tubular components to prevent component leads from transmitting stress to conductor pattern. Swaging or bending leads as shown minimizes chance of foil pulling away from board.

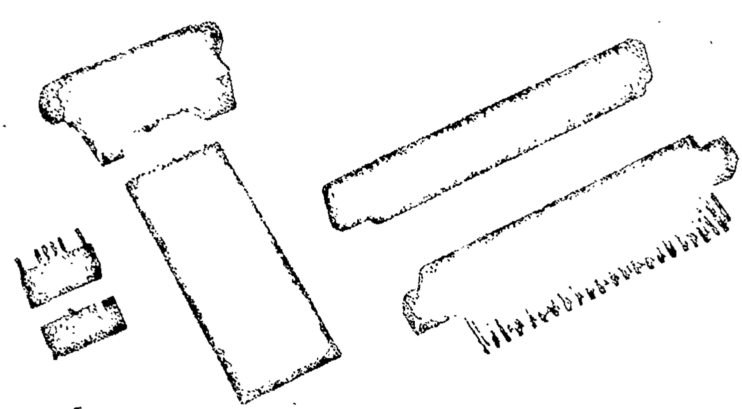


Fig. 4-12. Some of the types of connectors developed for printed wiring boards. (Product Engineering.)

advantageous to separate the wiring into more than one printed wiring board, containing functional component groups, for easier servicing of the equipment. Size is also determined by efficient use of the full laminate sheet, which varies among manufacturers, by processing and by assembling equipment. See Table 4-8.

Conductor spacing is governed by the voltage between conductors vs. leakage under moisture and altitude conditions anticipated. See Fig. 4-6. Maximum voltage and leakage resistance may determine the type of material to be used. The schematic should always be examined to determine the d-c and a-c voltages between any two conductors.

Processing and operating conditions play an important part in the selection of the board and the layout of the circuit itself. High ambients require laminates better than XXXP. If operation must be maintained in highly humid atmospheres, a glass-cloth base material is probably most suitable. Low barometric pressure from operation at high altitudes is a cause for greater arc-over possibility. Final potting or embedment may be considered.

For conductors, copper foil is available in 1/2 ounce, 1 ounce, 2 ounces, and 3 ounces per sq ft thicknesses in both electrolytic and rolled types, 1 and 2 ounces being by far the most common. Nonstandard thicknesses are also available. Temperatures above 1?0 C call for plated copper or noncorroding metals. Current rating commonly used for the design of conductors is the value that causes a 10 C rise above room temperature of 25 C but this is not standardized (Fig. 4-5).

The determining phenomena in the concept of conductor temperature rise are: (1) the maximum permissible operating temperature of the adhesive, (2) the minimum permissible bond strength, and (3) the extreme ambient temperature in a given application.

The rating given above for the design of conductors should be considered in the light of the following experience of the Bureau of Ships with coated board materials: (1) there is a ... to 20 percent reduction in the current carrying capacity compared to uncoated bare, (2) the surface and the conductor resistivity varies more widely and over greater range than with uncoated materials, and (3) no coating entirely prevents the formation of corrosion.

Step-by-Step Procedure for Layout

A logical approach to satisfactory layout is the breadboard technique, which can be used to simulate the eventual printed circuit. For preliminary design and test purposes, the following steps are recommended:

1. Obtain necessary components to produce the first sample.
2. Place all components on a sheet of cardboard or plastic transparency as close as possible to function in order to determine the minimum area of the circuit. Consider the size of components with leads that have been cut and formed.
3. Determine and sketch the most desirable shape for the circuit board with regard for its length, support, warp and so forth, within the limitations of a given material.
4. Cut the template to the desired shape, leaving it at least 25 percent larger than the minimum area previously determined.

Table 4-8—Characteristics Set by Assembling or Fabricating Means

System or machine	Board size (in.)	Component spacing (in.)	Hole diameter (in.)
GE automatic component assembly	max 8 × 12	0.?0 min side-by-side staggered	—
General Mills, Autofab	max 10 × 10, min 2	--	—
United Shoe Machinery	max 5 × 8	--	—
Melpar, Mini-Mech	1.6 × 2.1*	0.9 and 1.3 lead spacing	0.063
Erie, PAC	--	0.300 staggered, rows 0.100	--
RCA perforator	max 5 × 17.5	0.10 grid	0.053
Zaser multiple drill	--	--	min 0.100 C-C

* A new version accepts 6 × 6 approx.

5. Decide where the input and output stages and terminations should be located.

6. Locate all tube sockets beginning approximately with the input stage and following the order of the schematic (left to right) to the output.

7. Place in position all components, as determined by mechanical considerations, including cabinet and mountings.

8. Locate all large components as closely as possible to their schematic order.

9. Draw a tentative layout of the long unbroken conductors, such as filament and ground. Use the insulated body of the components to achieve crossover connections when required; this eliminates the necessity for two-sided patterns or wire jumpers by simply straddling one or more conductor patterns.

10. Lay out plate and grid connections with their associated components so that the leads are isolated. Utilize grounded areas of pattern between the plate and grid lines to act as an electrostatic shield.

11. Complete the design by laying out all the remaining conductors and components. Rearrange components if necessary. Conductors may be changed and rearranged; but by following the simple principles of this approach, the changes required should be few and minor in nature.

Testing the Layout

It is desirable to test electrically this first breadboard model. To do this: (1) select a piece of unclad plastic of the type to be used; cut it to the size and shape of the cardboard model. Place the cardboard over the plastic; and utilizing a sharp instrument, locate the centers of all holes through the cardboard with a scriber, marking onto the plastic beneath. (2) Drill holes in the plastic. Mount hardware and components. Bend pigtails of small components at right angles and push through holes in the board. (3) Make electrical connections to all components with solid wire that may be insulated or uninsulated. The path of the bus wires should follow the sketched layout as closely as possible on the cardboard model to simulate the final printed circuit layout. This model can then be tested electrically and further modification made if desired.

Drafting the Master

Once the initial design in the breadboard has been made, the black and white master may be drawn. Standard tolerances can be utilized to advantage, as these are fairly well established (Table 4-9). Accuracy must necessarily start with the master drawing, as the final circuitry is a direct photographic copy.

Materials used for a master drawing must have extremely good finish and high contrast for photographic copying. Conductor patterns should be drawn with black ink on dimensionally stable sheet. Bristol or Strathmore board may be used where close tolerances are not required, but for least distortion by temperature and humidity, Keuffel and Esser Stabilene or du Pont Mylar with a nonreproducible grid pattern is recommended.

Drawings are convenient at four times actual size, but other scales may be used depending on finished tolerances and precision to which the master drawing itself must be made. The scale, or at least one critical dimension, should be clearly indicated on the drawing as a guide for the reduction.

For economy and ease in dip soldering, line widths of 1/16 and 1/8 inch are best; the minimum practical limit is 0.030 inch. Numbers and letters should be drawn at least 1/8 inch high with a minimum line width of 0.020 inch when reduced (0.015 inch for photoetched). Hole centers, which are normally etched out and later used as spotting guides, should be blacked out and designated by a white dot (0.020 inch after reduction) in the center of the land pattern. A cross should not be used for hole center designations, as these tend to etch unevenly from piece to place.

The diameter of copper terminal areas in the actual printed circuit pattern should be at least 1/16 inch larger than the hole size. Due to undercutting during etching, the actual drawing should be made 0.002 inch wider per 0.001-inch thickness of copper for actual size required after etching. Fillets should be used at all points where a conductor line joins the terminal areas surrounding a hole. Borders not less than 1/32 inch wide should outline the board on the master drawing. If the border is not to appear in the finished product, the drawing should be made so that the inside edge of the border is on the outside edge of the board when finished. No circuitry should be indicated closer than 1/32 inch to the outside edge of the part unless it is absolutely necessary.

Two-sided patterns are best made by drawing the most critical side first. When opaque board is used, critical points may be located for the second side by utilizing pinholes

through the board. The second pattern can be accurately drawn to the back side of the same sheet for proper registry. Edge notches or two special guide holes in the final circuit layout may be required to carry registry through fabrication.

Registry in the master is carried (see Fig. 4-13) by a good optical system to a stable film base such as du Pont Kronar. This negative may be multiplied by a step-and-repeat camera, but its pattern is transferred by contact photoprinting to the sensitized clad surface with very little loss of definition.

It is necessary to have an engineering drawing supplementing the black and white master, specifying material and all mechanical dimensions.

Mechanical Fabrication

Printed circuits made on bases of high-pressure laminates can be drilled, blanked, sheared, sanded, routed, and postformed. Heavier stock can be drilled and tapped.

Drilling. Carbide tip drills give best performance for long runs and deep holes at faster spindle speeds. Normally, high-speed steel drills may be used with 30-degree lip angles. For thicker sections and deeper holes, the 45-degree angle is more desirable. Lip clearance should be around 15 degrees. It is necessary to clear away chips, which may be done by air jet. For XXXP materials, drills are used at the highest speed possible without burning, a 1/4-inch drill at 2500 rpm to 10,000 rpm for a No. 60. Where tolerances are close, oversize drills may be required. Jigs should be made with a plate beneath as well as a cover plate to prevent breaking out. Glass-base materials require carbide drills.

Punching or Blanking. Laminates are easily punched without lubricant, but most must be warmed. Standard punching processes are used with progressive compound or multiple dies. Phenolic paper may be punched at speeds as high as 300 strokes per minute; for a smooth edge the piece to be punched should be heated, regardless of thickness, to a maximum temperature on the heating oven of 250 F. Punches and strippers fitting closely with the compression stripped plate are recommended. Progressive dies are satisfactory but best results are obtained with compound dies. When stock is heated, an allowance must be made for shrinkage; blanking punches should be 0.001 to 0.008 inch smaller than the size of the thinnest blank, and spacing be-

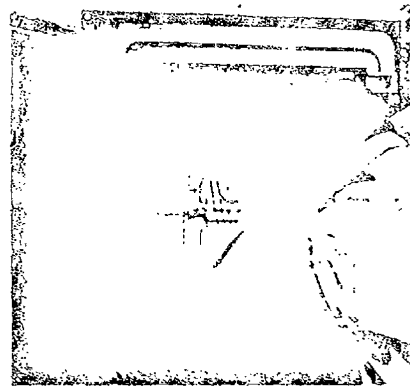


Fig. 4-13. Checking definition and registry of the master drawing on the ground glass of the photocopying camera. (Precision Circuits.)

tween punches should allow for shrinkage from 0.002 to 0.012 inch per inch depending on the thickness, the grade, and the heating temperature involved. It is always wise to check for allowance by testing a piece of the stock to be punched at the punching temperature, and checking dimensional changes with and across the grain. A rule (often violated in printed circuits) is that the holes shall not be smaller in diameter than one-half the thickness of the sheet. Square corners should be radiused.

Shearing. XXXP cold punching grades and many of the other phenolic clad laminates can be sheared, utilizing ordinary hand or power operated shears. The guillotine type is extremely efficient where large quantities are involved. Thicker sheets should be heated to approximately 120 F to give a clean cut; most clad phenolics can be cold sheared in thicknesses up to 3/32 inch.

Sawing. Paper- or fabric-base materials may be bandsawed where close tolerances or smooth edges are not important; otherwise, a hollow-ground circular saw without set should be used. The saw must be kept sharp to prevent chipping. Abrasive wheels are desirable for glass-fiber stocks, or carbaloy inserted tooth circular saws.

Post-forming. The post-forming operation for printed circuitry is complicated. Many times the circuitry pattern becomes ruptured or slides during the operation. The application of heat is extremely critical. It is desirable to avoid post-forming operations where printed circuits are concerned; but gentle curves may be made, to some extent,

Table 4-9—Standard Printed Circuit Tolerances in Inches

1. Unplated holes—diameter tolerances

Drilled			±0.003
Reamed			±0.001
Counterbored or flycut (dia from 5/16 in. to 4 in.)			±0.005
		Paper base	**Glass base**
Punched* (1/16 in. thick)	Up to 1/4-in. dia.	±0.003	±0.003
	1/4-in. to 1/2-in. dia.	±0.003	±0.004
	1/2-in. to 1-in. dia.	±0.004	±0.004
	over 1-in. dia.	±0.005	
Add ±0.001 to above for thicknesses of 3/32 in. through 1/8 in.			
Routed slots and notches up to 2 in.			±0.005
Milled or broached slots and notches up to 2 in.			±0.003

*Punched slots and notches: Use tolerances as above, considering both length and width as hole diameters.

2. Plated holes—diameter tolerances

Add the following tolerances to tolerances shown above on drilled or punched holes:

Drilled, paper base	±0.004
Drilled, glass base	±0.005
Punched, paper base	±0.003

3. Location tolerances on dimensions between holes (plated or unplated)

Drill by eye or "throw away" drill jigs	±0.015
Drill by pantograph or short-run drill jigs	±0.010
Drill by jig-bored hardened drill jigs	±0.005
Punch by RCA tape-programmed punching machine	±0.005
Punch by Wiedemann short-run template	±0.010
Punch by Wiedemann steel jig-bored template	±0.005
Punch by standard piercing die*, on dimensions up to 2 in.	±0.005
Add ±0.001 for every inch over 2 in.	

4. Hole to pattern tolerances (one side)

	Hole	
	Unplated	Plated
Drill by eye to pattern (sample runs only)	within 0.010 of center	—
Drill by temporary drill jigs or pantograph	within 0.020 of center	within 0.020 of center
Drill by permanent jigs	within 0.015 of center	within 0.015 of center
Drill by special visual alignment jigs	within 0.005 of center	—
Punch by RCA tape-programmed punch	within 0.015 of center	within 0.015 of center
Punch by Wiedemann short-run template	within 0.020 of center	within 0.020 of center
Punch by Wiedemann steel jig-bored template	within 0.015 of center	within 0.015 of center
Punch by standard piercing die	within 0.015 of center	within 0.015 of center

Table 4-9—Standard Printed Circuit Tolerances in Inches (cont)

5. Circuit pattern to outside dimension	
Routed edges	regular ±0.015; premium ±0.010
Turned O.D.	regular ±0.015; premium ±0.010
Blanked edges	±0.015
Milled edges	±0.015
All registry tolerances are predicated on usage of an accurate black and white master drawing made on dimensionally stable drafting material.	
6. Overall dimension tolerances	
Sawed edges	by eye ±1/32; with jig ±0.010
Routed edges	regular ±0.010; premium ±0.005
Turned O.D.	regular ±0.005; premium ±0.003
Blanked edges	±0.003 plus ±0.001 per in. of length
Milled edges	±0.005
Sheared	±1/32
7. Holes to outside dimension tolerances	
With progressive die	±0.010
With compound die	±0.005
Drilled and routed	±0.010
Drilled and routed, premium	±0.005
Saw by eye	±1/32
Saw by jig	±0.015
I.D. to O.D: regular T.I.R.†	0.010
premium T.I.R.†	0.003
8. Line width and spacing tolerances	
No plating, exclusive of nicks	regular ±0.010; premium ±0.005
With plating, exclusive of nicks	regular ±0.010; premium ±0.008
Min. line width and/or spacing: unplated	0.020
plated	0.020
melacon	0.025

* A high-precision ground die will reduce this by ±0.003.

† Total indicated runout.

even with other nonpost-forming grades such as N-1 and LE.

Design of Switches, Commutators

Switch elements designed integral to printed wiring, Fig. 4-3, may eliminate a considerable number of soldered joints. Phenolic laminates may be used successfully for low voltages; but if any arcing occurs, the effect is cumulative by carbonization, and better laminates are indicated. In conventional nonflush circuits, arc and brush bounce may be reduced by locating the switch elements closer together than the width of the brushes. Alternatively, the brush may be lifted by a d tent cam in passing interstices or a nonconnected segment (grounding to rotor, optional) may be between active segments to yield nonshorting types.

Active switches and commutators require enduring plated surfaces and are preferably of flush surface design. Rhodium is the common workhorse coating, but at high frequencies, nickel-rhodium may introduce some noise due to ferromagnetic effects.

In this case, solid silver foil or silver plating is recommended. Nickel plating may also be found useful. Indications of the life of various combinations of metal and base stock are given in Table 4-10. Gold alloys, cobenium wire, and plated phosphor bronze brushes, when operated with contact pressures between 3 and 40 grams, give the most satisfactory wear resistance as brushes.

Finishing

Protection of the solderability of copper circuits up to the point of soldering has never been ideally solved. No plate, except possibly silver, can be applied to the copper before lamination without interfering with etching, and silver does not retain its solderability well in storage. Plating after etching, unless carefully supervised, may also affect bond

Table 4-10—Characteristics of Printed Circuit Switch Plates

Copper conductor pattern	Plating	Plastic base	3/4- to 1-1/2-in. radius		Typical application
			Speed range (rpm)	Life range in revolutions	
Raised	0.001- to 0.003-in. silver	Phenolic or epoxy	Up to 300	Up to 1,000,000	Hand-operated detent switches, high frequency switches
Raised	0.0005-in. nickel with 0.000005-in. rhodium	Phenolic or epoxy	Up to 500	Up to 5,000,000	Servo mechanisms, commutators, slip rings, stepping switches
Raised	0.0005-in. nickel with 10- to 20-millionths rhodium	Phenolic or epoxy	Up to 500	Up to 50,000,000	Servo mechanisms, commutators, slip rings, stepping switches
Flush	0.0005-in. nickel with 20- to 40-millionths rhodium	Photocircuits black melamine surfaced composite laminate	Up to 2000	Upwards of 50,000,000	High speed, low torque, bounceless applications

and insulation. For these reasons, techniques are now in use that selectively plate with solder or gold prior to etching, and use the plated surfaces as etching resists. A summary of advantages as well as limitations of coatings is given in Table 4-11. Gold, if used, is generally plated thinly over plating nickel or tin-nickel (barrier layers against plating diffusion of gold into the copper) to reduce cost.

Special Reliability Determinants

The more commonly noted defects to be encountered are itemized in the list below; other items are not so generally recognized. For instance, in the effort to remove other contaminants, deleterious solvents are often inadvertently used.

Ordinary Inspection Defects:

In foil used for conductors:
- pinholes
- lead inclusions

In etched conductors:
- pinholes or notches due to thin resist
- blisters due to over baking resist
- leakage due to alkaline cleaners
- warp due to base stock or design
- scratches due to handling
- stains from processing or handling

In fabricated circuits:
- drilling burrs (due to hard spots in electrolytic foil)
- dimensional changes during hot punching
- eyelets not clinching base stock
- breakout of hole or eyelet

In finished circuits:
- low bond from solvent cleaning or baking
- blistering from hot tinning
- bond undercut during alkaline cleaning or plating

In assembled circuits:
- blistering or low bond due to soldering
- warp due to soldering temperature too high for the laminate
- inadequate solder fillet
- poor solder capillarity in oversize holes
- corrosive flux used

Deleterious Solvents. In cleaning, processing or punching, hydrocarbon oils, greases, and chlorinated solvents will attack the base laminate, particularly one of the silicones, such as G-6 and G-7, causing swelling or impaired adhesion of conductors. Ketones are generally recognized by NEMA as softening punching grades. Adhesives used on some XXXP and other stocks are also affected by benzol, xylene, or chlorinated compounds. Trichlorethylene is particularly suspect even when other related degreasers may be tolerated. If doubt exists, the sensitivity can be determined by checking the tendency to be sticky on sample surfaces from which the metal has been mechanically ripped, or more precisely, by measuring the peel strength of 25-mil lines before and after 30-minute exposure.

Plating Chemicals. G-5 is susceptible to dilute acids, which precludes etching in HNO_3.

Table 4-11—Solderability in Decreasing Order

Coating	Limitation
Tin-zinc plate	Zinc weakens joints
Gold	Expensive
Silver (clean)	Stores poorly
Cadmium (clean)	Stores poorly
Copper (clean) Lacquered copper	Stores poorly Operates irregularly
Tin (hot dipped)	Heat weakens bond
Tin plate (clean)	Variable
Solder plate	Compromise
Lead	Poor soldering
Cadmium plate (oxidized)	Poor soldering
Copper (oxidized)	Poor soldering
Silver (tarnished)	Poor soldering
Tin plate (oxidized)	Poor soldering
Nickel plate	Poor soldering
Brass	Poor soldering
Chromium	Poor soldering
Aluminum	Poor soldering

Any polymer, and particular adhesives, may be regarded as softened by strong alkali, unless proven otherwise. To some extent all alkaline electroplating deteriorates insulation and is better when specified before etching. Reverse current alkaline electrocleaners are particularly damaging to epoxy clad bond strength. Alkaline cleaners alone are not damaging to bond strength, but their complete removal is difficult and insulation troubles result if they are not completely removed.

Silver Migration. This is a phenomenon of rather rare occurrence that produces shorts in closely spaced wiring on either organic or inorganic insulation. In this phenomenon, silver electrolytically grows fine filaments across the gap. Very moist conditions are required—in the laboratory an actual film of water from 90 to 100 percent RH—plus the presence of silver, some soluble ions, a d-c potential, and considerable time. Soluble ions can be leached from most laminates, given high moisture and time. A summary of the facts of documented cases shows that migration occurs in the presence of about 1000 volts per inch, very high moisture conditions at 30 C, and in four years time. These occurred with silver-plated terminals in unclad laminates. No actual cases have been reported in plated circuits and occur with extreme rarity in any type of printed circuit, perhaps because overplating, normal solder coatings, and organic protectives retard its operation. However, silver migration is still considered a definite reliability hazard to printed wiring assemblies and must be considered, especially in equipment for use in military environments.

Miniaturization. Multiple-board assemblies are often designed in stacked, side-by-side, spokewise, in T, H, L, or eggcrate arrangements. If heavy components, like power transformers, are mounted on printed boards, they must be mechanically braced from steel supports. Subminiature tubes, if mounted flat on wiring boards, need thermal ground plates under them and preferably are held in thermal grounding clips. No specific structural guide can be given, but all multiple miniaturized assemblies must be rigorously analyzed for mechanical as well as thermal performance, as outlined by Bassler or tested out by the procedures suggested by Hannahs and Caffiaux. (9, 2)

Repair. Inexperienced servicing can lead to serious damage in printed wiring; elementary repairs, such as replacing a component, demand special techniques, principally in soldering. Force on a tube can stress and rupture conductors; dropping equipment sometimes fractures boards.

If at all possible, no repair soldering should be done on the actual printed conductors. The reason for this dictum can be found in the graph of hand soldering effects in Fig. 4-14. The results portrayed in the lower curve are from a 1/16-inch wide conductor on an excellent testing clad XXXP, running 16 pounds per inch bond strength, subjected to spot treatments with various irons, and subsequently incrementally examined for bond defect. Even with pencil irons, half the bond strength is lost at the point of soldering. Conductors on XXXP are specified only to endure 232 C for 10 seconds; unsoldering may require 3 to 10 seconds, and in 3 seconds conductors can reach 300 to 400 C, depending on the wattage of the tool.

If a conductor must be soldered, pencil irons should be used, and these preferably in series with a 150-watt lamp. Better procedure is to cut the old components leaving some leads projecting. One turn of the new component leads can be tightly wound around these stubs and soldered to the old leads.

A stripped or broken conductor can be jumped with hookup wire, drilling two fine holes—use light pressure and a motorized handy drill—to insert and anchor the ends if

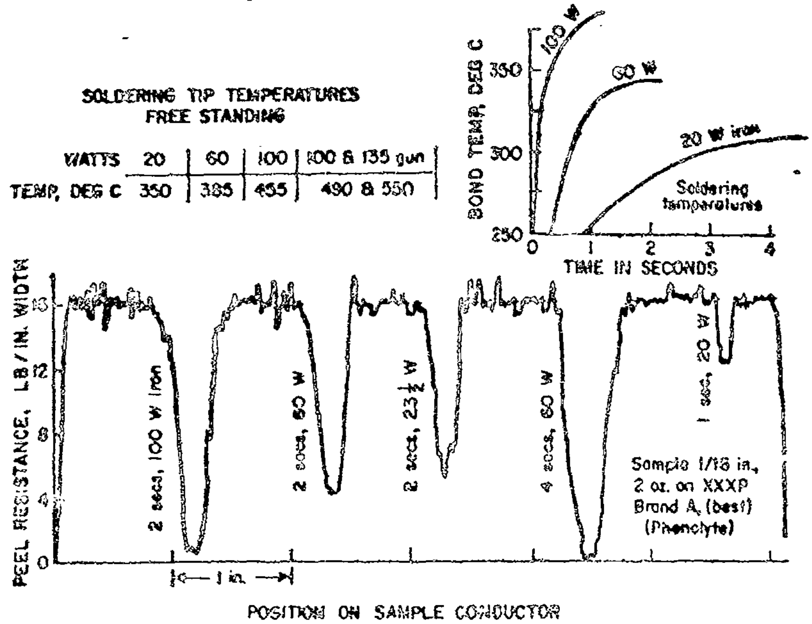


Fig. 4-14. Impairment of peel strength caused by hand (iron) soldering. (Sylvania Electric Products.)

needed. Conductors endangered or broken by a fractured board may similarly be repaired, and the board secured as well, by using short U staples of copper wire inserted and clinched in fine-drilled holes in the conductors to bridge the break and followed by soldering.

SPECIFICATION SOURCES

At the present writing, few performance limits are available from one agency. In absence of MIL specifications (an existing tentative specification was withdrawn) any present data are necessarily correlated from diverse sources using unstandardized methods. (EIA printed wiring subcommittees are currently obtaining standard test procedures, some of which are now in use to measure printed circuit properties and thus obtain data for limits.) Numerous properties of the common boards, of course, are derived from the characteristics of the base laminates for which there exists a NEMA standard.

1. MIL-P-13949A (Superseding MIL-P-13949, 25 January 1955) "Plastic Sheet, Laminated, Foil-Clad."

2. Technical Note, "Printed Wiring Techniques," Ro... Air Development Center TN-56-198, June 1954.

3. MIL-STD-429, "Printed Circuit Terms and Definitions," 13 December 1957.

4. "Standards for Laminated Thermosetting Products," NEMA LP 1 Part 7 (1956 Tentative).

5. "Technical Requirement for Protective Insulating Coatings for Auto-Sembled Equipment (Tentative)," Signal Corps Engineering Laboratories, 6 January 1956.

6. "Dimensional System for Automation Requirement," Signal Corp Engineering Laboratories, 11 May 1955.

7. "Design Requirements for Auto-Sembled Army Signal Electronic Equipment," Signal Corps Engineering Laboratories, Rev., 18 November 1954.

8. "Standard Method of Test of Adhesion of Printed Wiring," S.P. 484, March 1956, EIA Engineering Dept., New York 36, N. Y.

9. "Definition and Register, Printed Wiring," S.P. 508, August 1956, EIA Engineering Dept., New York 36, N. Y.

10. MIL-STD-275(Ships), 23 February 1956, "Printed Wiring For Electronic Equipment."

REFERENCES

1. Hannahs W. H., J. A. Caffiaux, and Norman Stein, "Standardization of Printed Circuit Materials," Tele-Tech, February 1954.
2. Hannahs, W. H., J. A. Caffiaux, and W. R. Wheeler, "Heat Transfer in Miniaturized Unit Assemblies," Sylvania Technologist, July 1950.
3. Hoynes, D. S., "Characteristics of Metal-Clad Laminates," Electrical Manufacturing, April 1957.
4. Martin, L. J., C. W. Mell, and M. J. Vavra, "Factors Determining the Reliability of Etched Wiring," Proceedings of the RETMA Symposium on Printed Circuits, January 1955.
5. Staudaher, F., "Results of Military Environmental Tests of Equipment Using Printed Wiring Assemblies," Proceedings of the RETMA Symposium on Printed Circuits, January 1955.
6. Report of the RETMA Conference on the Reliability of Electrical Connections, April 1954.
7. Proceedings of the Second RETMA Conference on Reliable Electrical Connections, Engineering Publishers, New York, September 1956.
8. Gamson, E. R., F. M. Hom and R. F. Newton, "Development and Application of Automatic Assembly Techniques for Miniaturized Electronic Equipment," Interim Engineering Report No. 6, Wright Air Development Center, July 1953.
9. Bassler, S. G. and M. Hinebaugh, "Principles of Electronic Circuit Packaging," Electrical Manufacturing, August 1955.

Contents

CHAPTER 5 SOLDERS AND FLUXES

Chapter 5

SOLDERS AND FLUXES

Although solder is not a component, it plays such an important part in the assembly of components into electronic equipment that the several alloys, fluxes, and techniques employed in the electronics industry are described here as general background for the equipment designer. Employed properly, solder makes permanent electrical connections that are inexpensive, nonporous, and unaffected by environment. The two metals joined by its use act as though they were one continuous metal. When the wrong solder, or the wrong flux, or the wrong techniques are employed, the best designed equipment will exhibit faulty operation or will not operate. A single open joint can do as much damage as a faulty component and is usually very much more difficult to locate.

Considering that there are thousands of soldered joints in any complex equipment (each one of which must form a solid, low-resistance electrical connection, impervious to moisture, vibration, or other environmental conditions), the skill with which each is made must be very high so that at least one will not be faulty. Most of these joints are man made, and the probabilities are just as great that a certain percentage will be defective as if each connection so made were an electrical component. Actually the chances are even greater since each component must go through numerous tests or inspections before it is installed, whereas each soldered joint is unique and cannot be tested for security before installation.

A description of the numerous alloys employed, the several current soldering techniques, the fluxes, some material on the effects of environment on solders and soldered connections, and some notes on printed circuit soldering will be found in this chapter. A considerable quantity of useful information has been abstracted from the current government and industry specifications and standards.

NOTE. Only rosin fluxes are recommended for electronic equipment connections.

SOLDERING PROCESSES

There are two general methods of using fusible alloys for joining metals. In soldering, the alloy is composed essentially of lead and tin in various proportions with certain other metals present for controlling the character of the alloy known as a soft solder. Only the solder reaches the molten state. The actual joining process takes place at a temperature below the melting point of the metals to be joined, 800 F being about the maximum temperature actually used.

In brazing, so-called hard or silver solders or brazing alloys are employed; the temperature required is much higher than for soft soldering, and actual fusion of the metals to be joined occurs. The higher temperatures required emphasize the fundamental difference between the soft solder and hard solder, or brazing alloy, techniques. The former consists in diffusion of a small amount of the metals being joined at temperatures below the melting point, while the latter represents actual fusion of the metals at or near the melting point. Soldering with silver solders or brazing alloys results in a joint of greater strength than is possible with low-temperature soldering.

AVAILABLE SOLDERS

Material Content

Soft solders contain predominantly tin and lead in some predetermined ratio chosen for the solder composition and physical characteristics which result from it. Also, soft solders contain varying amounts of antimony, bismuth, cadmium, zinc, or silver, which are added for varying the physical properties of the alloy. The hard or silver solders contain a greater or lesser amount of silver together with varying quantities of copper and zinc. In many solders, some of these elements, especially antimony, are present only as impurities.

Recent studies indicate that a minimum of 0.1 percent bismuth and 0.1 percent antimony are desirable in tin-lead solders to inhibit grey tin formation at low-temperature extremes.

Eutectic Point. The melting point of lead is 620 F, and that of tin 450 F, as shown in Fig. 5-1. In combining these metals, the addition of one lowers the melting point of the other. An alloy of approximately 63 percent tin and 37 percent lead results in the lowest melting point. This combination of the metals is called the eutectic composition. It becomes a liquid at the sharp and distinct temperature of 361 F and is in the plastic state, between solid and liquid form, over only a very small temperature range.

Low Melting Point Eutectic Alloys

Solder is available in compositions which will liquify at reduced temperatures. Such compositions are used when soldering delicate instruments and light gage wires which might be adversely affected by high temperature. Table 5-1 lists these alloys and shows a breakdown of their alloy components.

Tinless Solders

Although the vast majority of electrical joints connected by solder are made with tin-lead solder, other composition alloys are available. A solder composition of 97.5 percent lead and 2.5 percent silver has been found suitable for general purpose use for joining copper and copper alloys, iron, steel, and tin plate. Another solder used for a long time in the electrical industry for joining copper is 97.25 percent lead, 2.5 percent silver, and 0.25 percent copper. A 2-percent silver alloy is fairly standard. These solder alloys possess higher melting temperatures (about 580 F) than lead-tin solders, but produce improved creep strength.

Melting and Solidifying Temperatures

Solder alloys do not liquify immediately as the temperature is raised. They first become

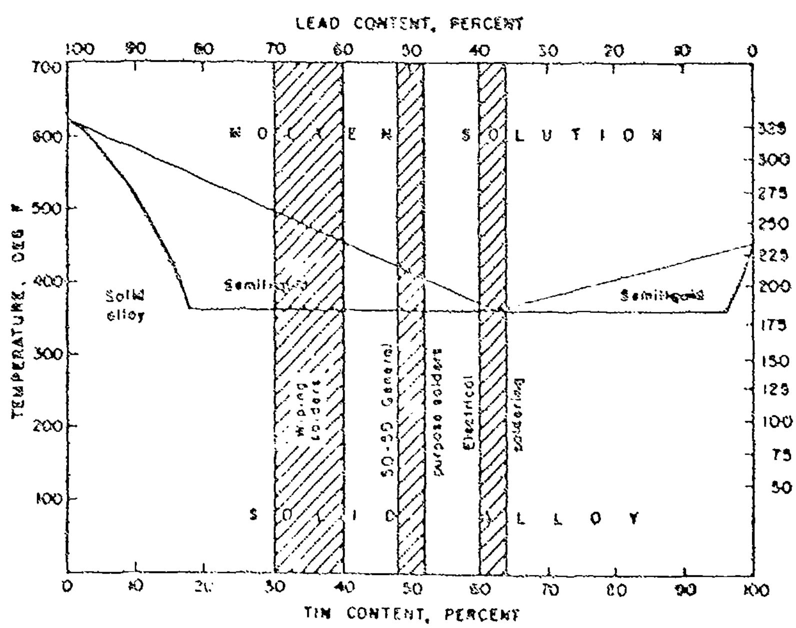


Fig. 5-1. Melting and solidifying temperatures, tin-lead solder alloys.

Table 5-1—Low Melting Point Eutectic Alloys

Melting point		Composition (%)				
(F)	(C)	Tin	Lead	Bismuth	Cadmium	Others
117	47	10.7	22.1	40.9	8.2	18.1 Indium
158	70	13.3	26.7	50.0	10.0	--
197	92.5	--	40.2	51.9	8.2	--
203	95	15.5	32.0	52.5	--	--
217	102.5	26.0	--	54.0	20.0	--
256	124	--	44.5	55.5	--	--
266	130	40.0	--	56.0	--	4.0 Zinc
281	138.3	42.0	--	58.0	--	--
288	142.2	51.2	30.6	--	18.2	--
291	144	--	--	60.0	40.0	--
351	177	67.8	--	--	32.2	--
362	183	61.9	38.1	--	--	--
390	199	91.0	--	--	--	9.0 Zinc
430	221	96.5	--	--	--	3.5 Silver
457	236	--	79.7	--	17.7	2.5 Antimony
477	247	--	87.0	--	--	13.0 Antimony

plastic, then semiliquid, and finally completely liquid. (See Fig. 5-1 and Table 5-2.) Most tin-lead solders enter the plastic state at 358 F, but become wholly liquid at various temperatures dependent on individual composition. Eutectic solder (63 percent tin and 37 percent lead) changes from solid to liquid at a single temperature point (361 F) without an intervening plastic state. Completely eutectic solders are not generally desirable because they lack plastic range, and are susceptible to fracture from slight vibration while cooling.

Shape

Solder is available in numerous physical forms. It is supplied commercially as a bar, stick, foil, wire, strip, or powder. Selection of a specific size and mass depends on the metal areas to be joined. Large conductors may require the bar or stick solder; small electronic components are most frequently joined by wire solder available in a variety of gages. Alloy content may be specified over a fairly wide range after characteristics such as melting point, tensile strength, and shear strength have been considered.

1. Solid. Solid solder may be procured in bars, ingots, drops, solid wire, or other forms.

2. Flux core. Flux-cored wire solder may be procured in numerous wire gages, alloy contents, and flux compositions (1)

3. Preformed shapes. Preformed solder can be supplied in pellets, washers, rings, coils, squares, triangles, and other shapes. The use of preformed solder shapes in production-line soldering is increasing. Pre-

Table 5-2—Melting Range vs. Composition

Nominal composition		Melting range (deg F)	Typical uses
Tin (%)	Lead (%)		
4	96	560-600	Coating metals and differential soldering
10	90	515-575	Coating metals and differential soldering
15	85	435-555	Coating and joining metals
30	70	361-495	General use solder
33	67	361-485	General use solder
38	62	361-465	General use solder
40	60	361-460	General use solder
45	55	361-440	Hermetic sealing
50	50	361-415	Special soldering applications
60	40	361-370	For low-temperature soldering
62	38	361-361	Eutectic solder of fixed melting point
75	25	361-380	Special soldering application

forms minimize solder consumption, permit the preassembly and soldering of several joints at one heating, and enable solder joints to be made at circuit points normally inaccessible to conventional soldering methods.

FLUXES

All common metals are covered with a nonmetallic film, usually an oxide of the metal, that prevents them from touching each other intimately enough to be really joined in the soldering process. The purpose of the numerous fluxes available is to remove this oxide surface so that the metals can be wet by the molten solder. The flux is not, or should not, be a part of the soldered connection at any time but merely serves to produce a bare metal-to-metal contact. Poor soldering techniques, however, have often produced rosin joints in which the flux material was not wholly removed in the process so that a high-resistance connection resulted, which had poor mechanical strength.

GOOD SOLDERING TECHNIQUE

Soldered joints of low electrical resistance and high mechanical strength can be produced only by the use of these few steps:

1. Utmost cleanliness
2. Good mechanical connection before soldering
3. Use of the proper solder alloy for the job
4. Use of the proper flux for the job
5. Proper temperature
6. Proper timing
7. Good inspection and cleaning

It is worth noting at this point that rosin is the only flux that will give long life and freedom from corrosion and noise. No other flux is recommended for electronic assembly.

SOLDERING METHODS

Soldering as an art and a technique is very old and takes various forms. Although some scientific effort has been expended on alloys, the fluxes, and the methods of applying them good soldering depends largely upon the skill of the operator. The first job of the apprentice to the tinsmith is to learn how to wield the massive irons, to apply solder to the materials to be joined, and to heat them properly in the blow torch. In the electronics laboratory, the technician must soon master the business of making good electrical connections with the hand iron or gun.

Most connections today are still made by hand either by means of a hand-held gun or iron or by use of induction or resistance heating. A comparatively recent development is the technique of making many connections at one time by means of dip soldering.

Hand Iron and Gun

Soldering with an iron or gun is preferred for intricate and complex connections. This technique gives the operator maximum control over the finished joint in terms of applied heat and amount of solder permitted to flow. Individual attention can be given to each separate connection without disturbing or interfering with adjacent points. The application of heat may be localized to a very small area. The hand iron has a high-resistance heating element and a relatively massive tip. As normally used, it reaches soldering temperature slowly and holds its temperature constant. Operated by a trigger switch, the gun consists of a step-down winding with a secondary of large cross section for high current. Its relatively low-resistance tip reaches soldering temperature rapidly. The small tip of the soldering gun permits concentration of its heat at the solder joints so as to prevent heat damage to surrounding components.

Dip Soldering

By this technique, numerous joints are prepared in advance by tinning or fluxing or by merely making tight mechanical connections. Then these joints are dipped, all at one operation, into a bath of molten solder to such a depth that all connections are soldered simultaneously. (2) This method is adapted to mass production and the parts to be soldered must be designed and assembled for this purpose. Thus, the components are mounted on a nonconductor base and made mechanically secure by one means or another. See Fig. 5-2.

Printed circuit assemblies lend themselves to this soldering technique. The eutectic composition of tin-lead solder is the most generally acceptable for dipping techniques for printed circuits. An addition of from 1 to 3 percent silver has been tried as a means of lowering the melting point of the solder and increasing the strength of the joint between the copper on the terminal board and the component lead wires. While this lowers the melting point of the mixture nearly 17 F, only marginal improvement is achieved in joint strength. Silver-loaded solders have been used primarily in soldering silver or

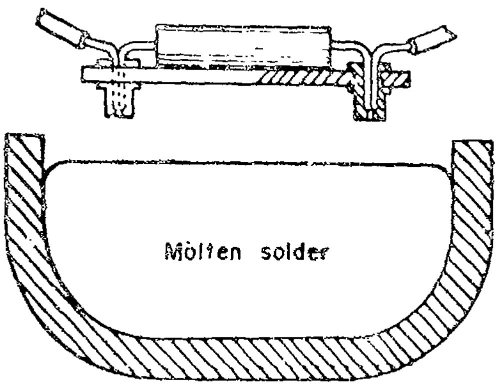


Fig. 5-2. Dip-soldering bath.

silver-plated printed circuitry to counteract the tendency of silver to dissolve in tin-lead solders.

The types of fluxes that float on the molten solder are not suitable for military equipment because of their highly corrosive properties. Rosin-based fluxes would quickly vaporize or carbonize if floated on molten solder. Rosin flux applied to the joints just prior to dipping is a preferred technique. More details on dip soldering and printed circuit soldering appear later in this chapter.

Sweating

In this soldering technique, two metals are coated with flux, perhaps in a pattern of some desired configuration, and then heated by a large iron or blowtorch. The solder seeks the flux on the metals, even flowing upwards against gravity by capillary action to follow the flux pattern.

Resistance Soldering

In the electrical resistance method (see Fig. 5-3) the metals to be joined are heated by current supplied by a low-voltage transformer. (2) The metals to be soldered are commonly gripped between carbon electrodes. The heat is generated directly in the metal area to be joined. Resistance soldering is extremely fast; in most cases 20 to 30 percent faster than the electric soldering iron method.

Induction Soldering

In this method (see Fig. 5-4) heat is generated within the work, rather than by the application of heat to the work. The heat required is produced by exposing the parts to be joined to the electromagnetic field produced by a high-frequency current. Eddy currents induced in the metals heat them rapidly. Induction soldering is particularly useful in working with large or massive pieces of metal. It is also useful in heating small intricate pieces of light gage metal which might oxidize excessively if heated by a flame.

Details of the several techniques or methods are described later in this chapter for the engineer who may have to set up a soldering line, or instruct operators under his guidance.

Solder-Joint Formation

By the accepted theory of solder-joint formation, after the wetting process a chemical alloying action occurs between the solder and the metal surfaces being soldered. (3) When soldering copper or brass, the alloy formed varies from 0.003 to 0.005 inch in thickness, and is stronger than pure solder. Two parallel surfaces separated 0.005 to 0.010 inch which are soldered are actually connected by the solder base alloy. However, when the spacing between the surfaces exceeds the alloy thickness, the alloy layers are separated by a layer of relatively pure solder which reduces joint strength. In addition to

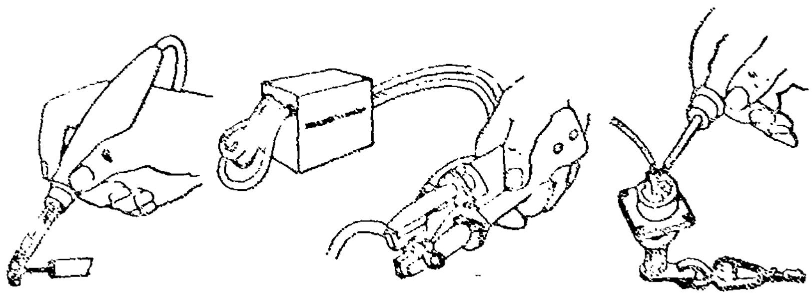


Fig. 5-3. Resistance soldering.

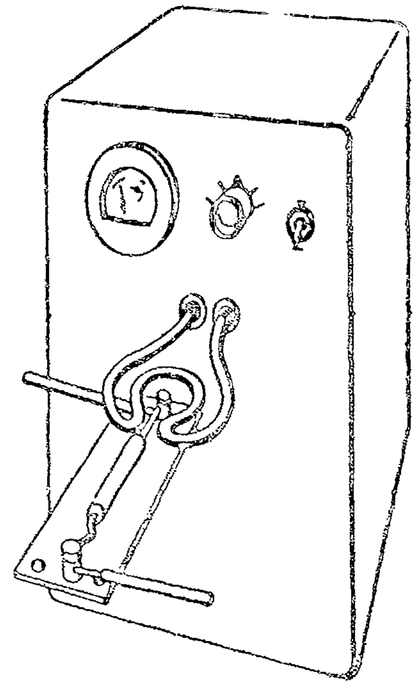


Fig. 8-4. Induction soldering.

the alloying action, a part of the strength of a solder joint is often attributed to interfacial contact generally analogous to the forces which will hold gage blocks together.

The base metal surfaces on a printed dip-soldered joint are perpendicular to each other rather than parallel. Therefore, according to the theories, the dip-soldered photo-etched joint consists largely of pure solder, and its strength is the strength of the solder.

SOLDERING TO SPECIAL SURFACES

Silver Coated. A silver-bearing solder is recommended for soldering to silvered surfaces. If a conventional tin-lead solder is used on a silver-fired ceramic or other silvered surface, the solder dissolves the silver from the surface and no bond is formed, or at best, the bond is weak. Silver will dissolve in molten solder until the silver content is approximately 6 percent.

Aluminum. Aluminum soldering presents a substantial problem because the lead forms a galvanic couple with aluminum, in the presence of moisture, which is harmful to the stability and life of the joint. Also, aluminum oxide, which forms a film on the surface of aluminum, can never be completely removed. Vigorous wire-bruching or some form of abrasive cleaning is required prior to soldering to get a satisfactory joint; and the oxide re-forms immediately upon exposure to air. Most aluminum solders contain tin and zinc and/or cadmium, and are used with special fluxes. Combinations such as 70 percent tin and 30 percent zinc or 60 percent tin and 40 percent zinc are commonly used. The melting point of these alloys is much higher than that of the tin-lead alloys, and heating by torch is necessary.

Glass-to-Metal. Indium with tin, lead, or silver, forms alloys of relatively low melting points which will wet glass and which are suitable alloys for soldering metal to glass. An alloy consisting of 50 percent tin and 50 percent indium, with a melting point of 241 F, is useful for this type of soldering.

Stainless Steel. Success in soldering stainless steel requires thorough removal of all surface dirt, rust, or organic material. Polished surfaces must be roughened with an abrasive wheel or cloth, and the residue wiped away with a clean cloth. Wherever possible, the areas to be soldered should be pretinned, especially those which require a noncorrosive flux in the final operation. Tin-lead solders can be used successfully for soldering stainless steel by using any of the customary methods. When using a soldering iron, a large tip should be used because of the low thermal conductivity of stainless steel. The tip should bring the base metal up to temperature, and the solder should be melted against the tip and permitted to flow into the joint. The iron should be moved across the joint at a rate that will permit the solder to flow freely into it. Overheating of the soldered members should be avoided since embrittlement of the stainless steel may occur if the temperature of the joint exceeds 700 F. Thin gage metals should be clamped together before soldering to prevent buckling or movement of the parts.

Stronger fluxes are required for soldering stainless steel than for more common metals. One suitable flux is saturated zinc chloride solution made by placing pieces of zinc in hydrochloric acid until the bubbling action stops. The residue from this or any other flux (excluding rosin) should be removed immediately following the soldering operation to prevent staining and further corrosive action. The joint should be washed with water containing soap, ammonia, washing soda (sodium carbonate), or other detergent.

Nickel. There are no special solders for nickel surfaces. Satisfactory results require good fluxing and soldering craftsmanship.

Galvanized Iron. In soldering galvanized iron, a alloy is used which contains less than 0.5-percent antimony. Antimony-free lead-tin solders are preferred. The flux is a mixture of ammonium chloride and zinc chloride.

Zinc. A cadmium-zinc alloy is satisfactory for joining zinc-base metals. Fluxing is unnecessary, but the surfaces should be free of foreign matter. Better intermetallic solution between the metals is achieved by first depositing a coating of nickel on the contact surfaces by an electrolytic plating method.

ADDITIVES AND IMPURITIES

Antimony. Solders compounded to any degree of remelted scrap metals generally possess some antimony. In any tin-lead-antimony solder, the ratio of antimony to tin cannot be greater than 0.0753 to 1. When this ratio is exceeded, clusters of tin-antimony compound crystallize during the cooling interval and cause brittleness in the finished joint. The maximum amount of antimony which can be held in solid solution by tin is 7.6 percent. In a solder alloy containing 50 percent tin, the maximum amount of antimony which can be tolerated is 3.8 percent. The use of antimonial solders has many disadvantages. They cannot be used on zinc or brass because of the formation of antimony compounds which produce brittleness. The ability of such solders to wet untinned surfaces is substantially less than that of antimony-free solders.

Zinc, Aluminum, and Cadmium. Zinc and cadmium are never added purposely to tin-lead solders for any application, with the exception of aluminum and zinc soldering. As little as 0.001 percent of either of these metals may cause grittiness or poor solder flow.

Copper. No appreciable trouble results from copper contents up to 1 percent of alloy total. Higher quantities above this value may cause gritty solder joints.

Bismuth and Arsenic. Small amounts of bismuth and arsenic can be tolerated, and seem to cause no bad effects on solder joints.

Silver. Silver normally is not present in solder except for special purposes. It is not harmful in small amounts.

COMPARABLE MECHANICAL TECHNIQUES

Several methods exist for making connections on small electronic components without the use of solder or the need for heat application. It must be remembered that a good mechanical joint should produce good metal-to-metal contact with the surfaces free from film or oxidation. High pressure between the conductors is necessary to provide gastight areas capable of withstanding weather and corrosion. The area of contact must be greater than the cross-sectional area of the conductor involved to avoid resistance and heating.

Pressure Connection

The pressure connection, shown in Fig. 5-5, is made by wrapping several turns of wire around a terminal lug. A commercial production-line device used in making this multiple twist is a hand-held gun that has a rotating spindle powered by compressed air or an electric motor. Rotation of the spindle causes the wire to wrap around the terminal in a tight helix, making a firm metal-to-metal joint. Contact pressure in the finished assembly is 15,000 psi minimum for the life of the connection; and with a perfect wrap, 24 contact areas are produced when using a rectangular terminal wrapped with six full turns.

Crimped Connection

In this type of connection, the terminal lug has a cylindrical sleeve which is slipped over the bare wire as shown in Fig. 5-6. The sleeve is then subjected to crimping by a tool to make a secure connection between the terminal and the wire. The actual crimping takes different forms in various commercial terminals; in some a single indentation is used while in others the entire periphery of the sleeve is compressed as shown in Fig. 5-7. It should be noted that when wire is released from compression in these methods, it expands slightly.

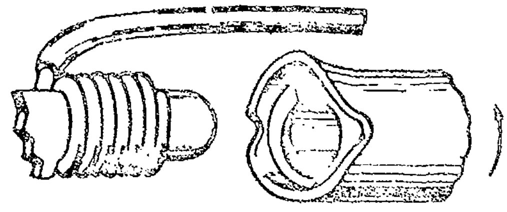


Fig. 5-5. Wire-wrap pressure connection.

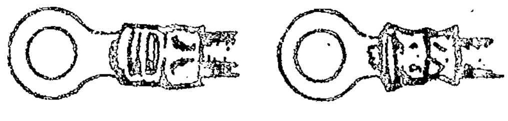


Fig. 5-6. *Crimped solderless lugs.*

As is true of soldering, these several methods for mechanically making electrical connections cannot take the place of screws, rivets, welding, or other methods of making a secure fastening. In particular, these methods must be looked at with great care from the standpoint of their vulnerability to vibration.

SPECIFICATIONS

Government

QQ-S-571b, Dated 30 September 1947. This specification covers soft solder (tin, tin-lead, and lead-silver) in the applicable physical forms and shapes required by governmental procurement agencies. (See Table 5-3.) Specification requirements relate to raw material content, chemical composition, and associated solidus-liquidus temperatures. Recommended applications of the solder alloys covered by this specification are:

1. Composition Sn70 is a special-purpose solder used where high tin content is required. It is intended for soldering zinc and for coating metals.

2. Composition Sn60 corresponds closely enough to the tin-lead eutectic to have a short melting range. Therefore, it is preferred for soldering electrical connections where temperature limitations are important and for coating metals.

3. Composition Sn50 is the customary "half and half" solder used in bit soldering and sweated joints in plain, tinned, or galvanized iron or steel, copper, and copper alloys. It is also used with soldered fittings in copper water tubing.

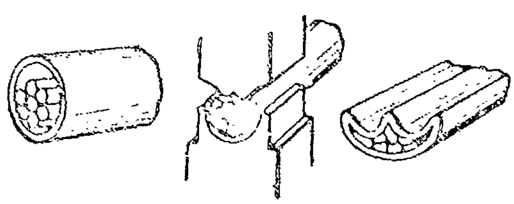


Fig. 5-7. Typical operation for forming crimped connections.

4. Composition Sn40 can be used for the same purpose as composition Sn50, although it is not as workable in bit soldering or coating. Composition Sn40 is frequently used for dip soldering and as a wiping solder.

5. Composition Sn35 is the common wiping or plumber's solder. Its higher antimony content promotes fine grain size in the wiped solders and in solders of greater strength than those without antimony.

6. Composition Sn30 is employed as an automobile-body solder for filling dents and seams.

7. Composition Sn20 is widely used as an automobile-body solder for filling dents and seams and for general purposes where a high tin-content alloy is not required, such as for protective coatings on steel sheet.

8. Composition Ag2.5 is not satisfactory on black uncoated steel sheet using any of the current soldering techniques. This solder requires higher temperatures and the use of a flux with a zinc chloride base to produce a good joint on untinned surfaces. A rosin flux is unsatisfactory for soldering untinned copper, brass or steel with this composition. This solder is susceptible to corrosion in humid environments.

9. Composition Ag5.5 will develop a shearing strength of 1500 psi at 350 F. The temperature of application should not exceed 850 F when soldering hard-drawn brass or copper. Composition Ag5.5 is used on thermocouples for aircraft engines where relatively high operating temperatures do not affect the strength of the solder. In other respects, the precautions noted for composition Ag2.5 are also applicable.

10. Composition Sb5 is used for electrical connections subjected to peak temperatures of about 400 F and for sweating copper tube joints in refrigeration.

Compositions Sn35, Sn30, Sn20, and Sb5 should not be used for soldering zinc or cadmium, or any metals coated with them, because the zinc and cadmium form intermetallic compounds with the antimony in the solder. These compounds have high melting points, and thus hinder the flow of solder and render the joints brittle.

Fluxes generally used with these solders are acid or rosin. Acid fluxes are more active in removing oxides from the base metal,

Table 5-3—Solder Compositions from Federal Specification QQ-S-571b, 30 September 1947

Composition* (%)											Approximate melting range (deg F)†	
Composition‡	Tin§ (range)	Lead (max)	Antimony (max)	Silver (max)	Copper (max)	Iron (max)	Bismuth (max)	Zinc (max)	Aluminum (max)	Total all others (max)	Solidus	Liquidus
Sn70	69.5-71.5	remainder	0.50	—	0.08	0.02	0.25	0.005	0.005	0.08	361	378
Sn60	59.5-61.5	remainder	0.50	—	0.08	0.02	0.25	0.005	0.005	0.08	360	372
Sn50	49.5-51.5	remainder	0.50	—	0.08	0.02	0.25	0.005	0.005	0.08	360	420
Sn40	39.5-41.5	remainder	0.50	—	0.08	0.02	0.25	0.005	0.005	0.08	360	460
Sn35	34.5-36.5	remainder	1.6-2.0	—	0.08	0.02	0.25	0.005	0.005	0.08	360-365	490-500
Sn30	29.5-31.5	remainder	1.4-1.8	—	0.08	0.02	0.25	0.005	0.005	0.08	[illegible]	500-510
Sn20	19.5-21.5	remainder	0.8-1.2	—	0.08	0.02	0.25	0.005	0.005	0.08	360	525-545
Ag2.5	—	remainder	0.40	2.3-2.7	0.30	0.02	0.25	0.005	0.005	0.30	580	585
Ag5.5	—	remainder	0.40	5.0-6.0	0.30	0.02	0.25	0.005	0.005	0.30	579	[illegible]
Sb5	94.0 min	0.2	4.0-6.0	—	0.08	0.08	Cadmium 0.03	0.03	0.03	0.30	450	464

* Specified percentage is for solder metal only. In flux-cored wire solder, the weight of the flux shall be subtracted from the total weight to obtain the weight of the solder metal.

† For information only.

‡ Tin-lead solders (prefixed by Sn) may be furnished as flux-cored wire as well as plain wire and other forms. The weight of the flux in rosin-flux-cored wire shall not exceed 4 percent of the total weight. The weight of the flux in chloride-flux-cored wire shall not exceed 6 percent of the total weight.

§ When tin-lead solders (prefixed by Sn) are furnished as flux-cored wire, the minimum permissible tin content shall be 0.5 percent less than the minimum values specified in the table.

but the flux residues are corrosive and must be removed after soldering. If it is not practical to remove the flux residues (for example, from electrical and radio parts), then rosin fluxes whose residues are not corrosive must be used. The parts should be cleaned of any heavy oxide films before assembly to compensate for the milder action of rosin fluxes.

QQ-S-561d, Dated 27 September 1951. This specification describes the physical forms in which silver solder may be supplied. Necessary workmanship qualities resulting from its use are cited. The chemical constituents of eight classes of silver solder are shown in Table 5-4. Their approximate melting points, flow points, and colors are shown in Table 5-5. The applications of each class of silver solder are:

1. Class 0 solder is intended for ordinary brazing purposes where a solder of higher physical properties is required than those provided by brazing (spelter) solders, and where the service or appearance does not require a high-silver solder.

2. Class 1 solder is high-grade solder intended for general silver soldering requirements.

3. Class 2 solder has a very high silver content and should be used only where the application requires high strength, resistance to corrosion, and good appearance.

4. Class 3 solder is intended only for brazing copper and copper-base alloys, and is not intended for use on ferrous alloys.

5. Classes 4 and 6 are general-purpose alloys for joining copper, brass, ferrous metals, and particularly nickel-copper alloys and alloy steels.

6. Class 5 solder is intended for those applications where the characteristics of Classes 4 and 6 are required, but where the design necessitates the addition of a fillet or where close tolerances cannot be maintained and the fillet is necessary. Class 5 is also intended for hard materials such as cemented carbides for tools.

7. Class 6A has physical properties similar to those of Class 4. When Class 4 is not available, use Class 6A. By following good practice, joints with tensile strengths in excess of 70,000 psi may be produced in carbon steel. Although the thermal properties of Classes 4 and 6A are similar, some modification of technique may be necessary because of the broader melting range of Class 6A.

8. Thin narrow strips of Classes 1, 2, 4, 5, and 6 solder should be used for very light work, such as soldering parts of delicate instruments.

Military

MIL-S-6872A, Dated 15 December 1954. This specification, approved and used by the

Table 5-4—Silver Solder Constituents from Federal Specification QQ-S-561d, 27 September 1951

Class	Silver, range (%)	Copper, range (%)	Zinc, range (%)	Phosphorus, range (%)	Cadmium, range (%)	Nickel, range (%)	Total other elements, (% max)
0	19.0-21.0	44.0-46.0	33.0-37.0	--	--	--	0.15
1	44.0-46.0	29.0-31.0	23.0-27.0	--	--	--	0.15
2	64.0-66.0	19.0-21.0	13.0-17.0	--	--	--	0.15
3	14.5-15.5	79.0-81.0	--	4.75-5.25	--	--	0.15
4	49.0-51.0	14.5-16.5	14.5-18.5	--	17.0-19.0	--	0.15
5	49.0-51.0	14.5-16.5	13.5-17.5	--	15.0-17.0	2.5-3.5	0.15
6	49.0-51.0	14.5-16.5	23.0-27.0	--	9.0-11.0	--	0.15
6A	49.0-51.0	17.0-19.0	20.0-24.0	--	9.0-11.0	--	0.15

Departments of the Army, Navy, and Air Force, is the general specification for the soldering process. It covers general requirements for making soldered joints by using filler metal with flow temperatures below 426 C (800 F). Reference is made to Specification QQ-S-571b (Solder; Soft) for solder alloy conformance requirements. Important aspects of this specification as of 15 December 1954 are abstracted as follows:

1. Preparation of surfaces. The surfaces of the parts to be joined shall be cleaned before the tinning or soldering operation. Oxides, scale, and dirt shall be removed by mechanical means, such as scraping or cutting with an abrasive, or by chemical means. Grease shall be removed by a suitable solvent, such as trichlorethylene. Except when insulated wire or cable is present, an acid dip may be used to remove scale or oxides, but a neutralizing treatment is required to prevent subsequent corrosive action.

2. Cleaning. Only mechanical cleaning shall be used for cleaning surfaces to be soldered for electrical wire connections. Other cleaning methods which will not leave a corrosive residue may be used after satisfactory completion of humidity tests.

Table 5-5—Melting and Flow Points of Silver Solder

Class	Melting point F	Melting point C	Flow point F	Flow point C	Color
0	1430	775	1500	815	Yellow
1	1250	675	1370	745	Nearly white
2	1280	695	1325	720	White
3	1200	650	1300	705	Gray-white
4	1160	627	1175	635	Yellow-white
5	1195	645	1370	638	Yellow-white
6	1160	630	1190	641	Yellow-white
6A	1160	627	1185	640	Yellow-white

3. Flux. After the joints have been properly cleaned and fitted, a thin even coating of flux shall be placed over the surfaces to be joined. The flux shall be capable of preventing oxidation of the surfaces while the parts are being heated to soldering temperatures. The use of cored wire solder is acceptable.

Flux shall be applied only to the surfaces to be joined. Splashing or dripping onto other surfaces shall be avoided. Corrosive flux shall not come into contact with any textile materials, particularly those containing cotton. Active fluxing agents shall not be used to clean soldering coppers when neutral fluxes are employed in making the joints.

4. Heating. The areas to be joined shall be heated to or above the flow temperature of the solder. Heat may be applied by soldering copper, torch, molten-alloy bath, electrical resistance, or other suitable means. The application of heat shall be carefully controlled during the soldering operation to prevent damage to components of the assembly, such as fabric, insulating material, and assemblies.

5. Individual tinning of parts. When the use of corrosive flux is necessary, it shall be standard practice to flux and tin with solder those portions of the surfaces to be joined prior to assembling, remove flux residues, according to schedule (see item 13 below), assemble the component parts, and use a neutral flux in making the soldered joint. This procedure is mandatory when the character of the materials is such that an active flux must be used to obtain a satisfactory joint, yet the action of the flux residues or removal will be detrimental to the parts of the assembly.

6. Wires soldered to terminals. Wires to be soldered into a terminal or receptacle should be tinned, then sweated into the termi-

nal or receptacle without adding more solder than is necessary to fill the space around the wire. Parts pretinned by the manufacturer need not be retinned before soldering.

7. Tinning. Tinning on a wire should extend only far enough onto the wire to take full advantage of the depth of the terminal or receptacle. Tinning or solder on wires outside the receptacle where flexing may occur will cause stiffness of the wires and result in breakage.

8. Surface heating. Solder should not be melted with the soldering copper and allowed to flow on a surface which is not thoroughly heated.

9. Temperatures. Excessive temperatures should be avoided or the flux will tend to carbonize and hinder the soldering operation.

10. Cooling. Liquids must not be used to cool a soldered joint. With the proper solder and soldering technique, a joint should not become so hot that it needs rapid cooling to prevent the wire insulation from charring.

11. Flux residues. After the joint has cooled, the residue from active fluxes shall be completely removed or neutralized. Removal of neutral flux residues will not be necessary, except on surfaces of electrical contacts and on other surfaces where the flux might interfere with the operation or assembly of the component.

12. Flux removal schedule.* The removal schedule includes as many of the following operations as are necessary to prevent corrosive action by the residues from active fluxes:

a. Remove oils or greases commonly used in paste-type fluxes with a suitable solvent, such as naphtha or trichlorethylene.

b. Dip in dilute acid solution with agitation. (Dilute hydrochloric acid, sulfuric acid, or sodium bisulfate solution are necessary.) The addition of an acid-active wetting agent will accelerate the action.

c. Wash thoroughly in flowing water.

d. Dip in dilute alkaline solution of a type and concentration suitable for use with the specific materials involved, and agitate.

e. Wash thoroughly in flowing water.

13. Production parts. Production parts shall be cleaned, fluxed, soldered, and residue removed in accordance with the approved soldering process and flux residue removing schedule.

* This removal schedule is not applicable to many electronic assemblies. Use of corrosive fluxes should be avoided.

Commercial

Designation B 32-49, ASTM. This specification covers thirty grades of tin-lead, tin-lead-antimony, and silver-lead solder alloys in commercial forms of soft solder. The required quality, chemical composition, and permissible variation in chemical composition of these alloys are given. Table 5-6 shows the alloy content of these solders.†

Standard for Solder, SAE. The Society of Automotive Engineers standard for solder defines twelve grades in terms of alloy composition and liquidus-solidus temperatures. The ASTM counterparts for six of the SAE alloys are given in the extreme right-hand column of Table 5-7.

FLUX TYPES

Although rosin-base fluxes are the only fluxes known whose residues are completely noncorrosive and electrically nonconductive and are the only ones that are universally acceptable for use in military equipment, the following material, mostly from J. Robert Milliron of Wright Air Development Center, is included as general background information.

Solder fluxes may be divided into three general groups: (1) rosin, (2) organic, and (3) chloride or acid. The last two are not generally used in making electronic circuit connections because of their corrosiveness. Rosin fluxes are most highly favored. Under some conditions the chloride types may be employed in electronic equipment.

Rosin. As used and defined in military specifications, these fluxes use a commercial grade WW rosin which, in its natural state, is a polymerized anhydride, a type of closed molecular structure where the rosin molecules are locked together in an inert form. The unique and enviable position that the rosin-type fluxes enjoy was achieved through a long period of test and from much experience. One of its draw-backs is its slow action and its inability to promote wetting of the surfaces of moderately oxidized metals.

† Recent studies indicate that a minimum of 0.1 percent bismuth and 0.1 percent antimony in tin-lead solders will inhibit grey tin formation in extremely low temperatures.

Table 5-3—Solder Composition,* Designation B 32-49, ASTM

Alloy grade	Tin (%)			Lead (nominal %)	Antimony (%)			Silver (%)			Corresponding SAE types†
	Min	Desired	Max		Min	Desired	Max	Min	Desired	Max	
70A	--	70	--	30	--	--	0.12	--	--	--	--
70B	--	70	--	30	--	--	0.50	--	--	--	--
60A	--	60	--	40	--	--	0.12	--	--	--	--
60B	--		--	40	--	--	0.50	--	--	--	--
50A	--	50	--	50	--	--	0.12	--	--	--	--
50B	--	50	--	50	--	--	0.50	--	--	--	--
45A	--	45	--	55	--	--	0.12	--	--	--	--
45B	--	45	--	55	--	--	0.50	--	--	--	1A
40A	--	40	--	60	--	--	0.12	--	--	--	--
40B	--	40	--	60	--	--	0.50	--	--	--	2A
40C	--	40	--	58	1.8	2.0	2.4	--	--	--	2B
35A	--	35	--	65	--	--	0.25	--	--	--	--
35B	--	35	--	65	--	--	0.50	--	--	--	--
35C	--	35	--	63.2	1.6	1.8	2.0	--	--	--	--
30A	--	30	--	70	--	--	0.25	--	--	--	--
30B	--	30	--	70	--	--	0.50	--	--	--	3A
30C	--	30	--	68.4	1.4	1.6	1.8	--	--	--	3B
25A	--	25	--	75	--	--	0.25	--	--	--	
25B	--	25	--	75	--	--	0.50	--	--	--	4A
25C	--	25	--	73.7	1.1	1.3	1.5	--	--	--	4B
20B	--	20	--	80	--	--	0.50	--	--	--	5A
20C	--	20	--	79	0.8	1.0	1.2	--	--	--	5B
15B	--	15	--	85	--	--	0.50	--	--	--	6A
10B	--	10	--	90	--	--	0.50	--	--	--	--
5A	4.5	5	5.5	95	--	--	0.12	--	--	--	--
5B	4.5	5	5.5	95	--	--	0.50	--	--	--	--
2A	1.5	2	2.5	98	--	--	0.12	--	--	--	--
2B	1.5	2	2.5	98	--	--	0.50	--	--	--	--
2.5S	--	0	0.25	97.5	--	--	0.40	2.3	2.5	2.7	S-07
1.5S	0.75	1	1.25	97.5	--	--	0.40	1.3	1.5	1.7	--

* For elements other than those mentioned in the table, the maximum content in the alloy is as follows (percent):

Bismuth 0.25

Copper { Alloy grades 70A to 2B incl. 0.08
Alloy grades 2.5S and 1.5S . . . . 0.3 }

Iron 0.02

Aluminum . . . . }
Zinc . . . . } each shall not exceed 0.005

Analysis must be made regularly only for the elements specifically mentioned in the table and footnote. If, however, the presence of other elements is suspected, or indicated in the course of routine analysis, further analysis shall be made to determine that the total of these other elements is not in excess of 0.08 percent.

† Chemical requirements conform substantially.

Rosin must be a solid to be noncorrosive. When melted by heating, it is very active. This activity persists as long as heat is applied, but stops when the rosin is again cold. A comparable situation exists when rosin is dissolved in any liquid. Depending on its dielectric constant, the solvent exerts an effect on the dissolved rosin which causes corrosion as long as rosin is in the dissolved state. However, when the solvent is volatilized by the normal heat of soldering, or by subsequent evaporation, the dry solid residue is noncorrosive and electrically nonconductive.

Table 8-7—Compositions and Temperatures, SAE Standard for Solders

SAE No.	Tin (%)	Lead	Antimony (%)	Temperatures			
				Solidus		Liquidus	
				F	C	F	C
1A	45.0, -1.0	Remainder	0.4 max	361	183	414	212
1B	43.0, +0.5	Remainder	1.5-2.00	361	183	403	208
2A	40.0, -1.0	Remainder	0.4 max	361	183	460	238
2B	38.0, +0.5	Remainder	1.5-2.00	361	183	450	232
3A	30.0, -1.0	Remainder	0.4 max	361	183	494	257
3B	28.0, +0.5	Remainder	1.5-2.00	361	183	484	251
4A	25.0, -1.0	Remainder	0.4 max	361	183	511	266
4B	25.0, -1.0	Remainder	1.25-1.75	361	183	502	261
5A	20.0, -1.0	Remainder	0.4 max	361	183	525	274
5B	20.0, -1.0	Remainder	1.25-1.75	361	183	518	27[illegible]
6A	15.0, -1.0	Remainder	0.4 max	361	183	543	284
6B	15.0, -1.0	Remainder	As specified*	361	183	532-541	278-283

* Maximum, 2.75 %

Activated rosin fluxes. Expansion of the electronics industry produced a demand for faster and more efficient soldering techniques. To meet the requirements several European manufacturers added acidic materials to the rosin and sold the mixtures as rosin fluxes. These fluxes were very corrosive and fortunately were not widely used in the U.S.A. During 1946 and 1949 several activated rosin fluxes were introduced and were used to some extent in this country. These modified rosins varied from mixtures of rosin and acidic materials to specially prepared resins or rosin to which other materials were added to improve the efficiency. The first activated fluxes contained ammonium chloride, zinc chloride, aniline hydrochloride, or naphthalamine phosphate. The activators currently being employed are usually halogenated organic compounds that may or may not be soluble in the resin. These activators include the following: aniline hydrochloride, naphthalene hydrochloride, carbon tetrachloride, cetyl pyridinium bromide, dimethyl cetyl ammonium bromide, ethyl dimethyl cetyl ammonium bromide, and so on. Competition among the flux manufacturers resulted in the production of activated rosin fluxes, which range from pure rosin to those of acid-type fluxes.

Activated rosin may be defined as a homogeneous resin prepared by the incorporation of a second substance, which may not have fluxing properties. It also has an activity greater than that of either pure single constituent at the same concentration. The theory of its action is controversial, but the best explanation is that the activating agent, at the heat of soldering, changes the anhydride structure with conversion and release of the free rosin or reducing groups with a high level of activity. An activated rosin must possess the following properties: (1) it must be physically and chemically homogeneous, and (2) it must be as noncorrosive and electrically nonconductive as the resin from which it was made, but must possess a higher activity.

No easy way has been found to test whether these fluxes are corrosive or not. A vast number of the activated fluxes are proprietary and there is much reluctance on the part of the manufacturers to disclose their contents. MIL-S-6872 requires the use of commercial WW rosin in denatured alcohol. All other fluxes are considered as active until demonstrated by test that the flux is neutral.

Organic Fluxes. These consist of mild organic acids and bases, and some of their derivatives. These fluxes are almost as active as the inorganic salts, but their period of activity is brief because of lesser stability and their susceptibility to thermal decomposition. They decompose rapidly under the heat of soldering. This offers a means to limit or control corrosion since the corrosive properties of the relatively inert flux residue are very different from those of the original undecomposed flux. These residues are not hygroscopic. They become dry and withered and are relatively easy to remove by flaking, tumbling, or wiping with a damp cloth. The speed and quality of soldering with organic fluxes compare favorably with those of chloride film. They are very effective and where

nominal amounts of corrosion may be permitted or where the assembly lends itself to residue removal, they may be used satisfactorily.

Chloride or Acid Fluxes. These are solutions of one or more inorganic salts, generally the chloride and occasionally the phosphate of zinc, calcium, aluminum, magnesium, or tin. The commercial designation of "acid" when applied to these fluxes is a misnomer since the fluxes are actually salts.

The chloride-type fluxes are the most active and are effective on all common metals except aluminum and magnesium. Of all fluxes, these are the most corrosive, and the corrosion seems to be caused by galvanic or electrolytic action. The hygroscopic character of the flux residue is possibly more important than corrosion. Although hard and dry immediately after soldering, the fused residue gradually absorbs water from the air which finally dissolves and dilutes it. This causes the residue to spread over a wide area of the soldered unit.

The hygroscopic character of the chloride type flux is useful in the removal of the residue after soldering. When the residue is softened by absorption of water, the soldered unit is treated with hot water or steam to dissolve and wash away the residue.

Where their use is not actually prohibited, acid or chloride fluxes must be used with extreme care in electronic equipment. When using corrosive fluxes, the hot soldering iron has a tendency to spatter the flux onto surrounding areas, which is another reason why they are not recommended.

No matter what flux is employed, its purpose is not to clean the surfaces but to remove oxide. Flux cannot replace good cleaning methods to produce bright metal surfaces with which to start the actual soldering operation.

PHYSICAL AND CHEMICAL CHARACTERISTICS OF SOLDER

Tensile Strength. The tensile strength of a solder alloy is the greatest longitudinal stress it can withstand without pulling apart or rupturing. This factor depends upon many variables, primarily temperature, the rate at which the load is applied, the physical configuration of the solder specimen, and the nature of its alloy. As shown in Fig. 5-8, tensile strength rises with tin content approximately to the 60- to 70-percent tin alloy composition where it measures nearly 8000 psi. The primary purpose of soldering is not to secure strength in a connection, but to form a permanent electrical joint with optimum environmental characteristics.

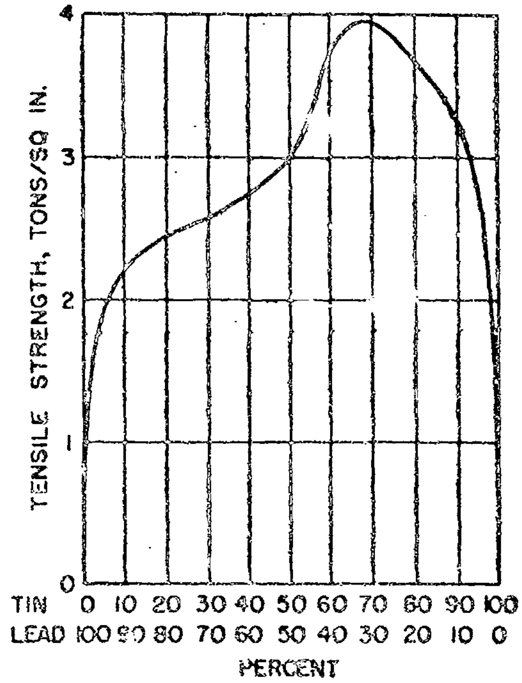


Fig. 5-8. Variation in tensile strength with tin content.

Shear Strength. The shear strength of a solder alloy is the greatest transverse stress it can withstand without rending or rupturing. This property is subject to the same governing factors which control its tensile strength. Shear strength, like tensile strength, is highest with solder alloys composed of 60 to 70 percent tin. The shear strength curve resembles the tensile strength curve, but all values are moderately reduced.

Hardness. The hardness of a solder alloy can be determined in several ways. However, if significant useful data are to be obtained, the importance of standardizing methods and environmental test conditions should be emphasized. The curve in Fig. 5-9 supplies hardness data obtained by the Brinell test with $L/D^2 = 5$, time of loading 30 seconds at 20 C on a chill-cast specimen about 1/4 inch thick, cast from 50 C above liquidus into mold at about 100 C.

As the characteristic curve indicates, hardness values of the tin-lead alloys ap-

proach maximum with 60 to 90 percent tin. When the nature of the metals to be joined permits its use, antimony in small quantity will increase the hardness of tin-lead alloy.

Thermal Conductivity. Dissipation of heat is an important property of a selected solder composition since it has a direct bearing on electrical conductivity. The electrical resistance of a solder joint is inversely proportional to the thermal conductivity. In applying solder to a joint, optimum thermal conductivity can be obtained by controlling the amount of solder deposited. The compromise point between physical strength and thermal conductivity of the joint occurs at about 0.004 inch in thickness. Solder deposits which exceed this dimension in conventional radio chassis wiring add little to the overall physical strength and electrical conductivity, and detract tangibly from the thermal dissipation capabilities in proportion to the excess. The thermal conductivity of solder is dependent to a large degree upon the amount of tin contained in the alloy. The curve of Fig. 5-10 shows thermal conductivity of solder as a function of tin content.

Corrosion. All soldering fluxes, except rosin and certain homogeneous resins, are corrosive and their residues are electrically conductive. The extent of corrosive action is determined by the final chemical equilibrium. At chemical equilibrium, the total amount of corrosion is comparable for all fluxes having equal volumes of corroding residue regardless of the rate at which they proceed to equilibrium.

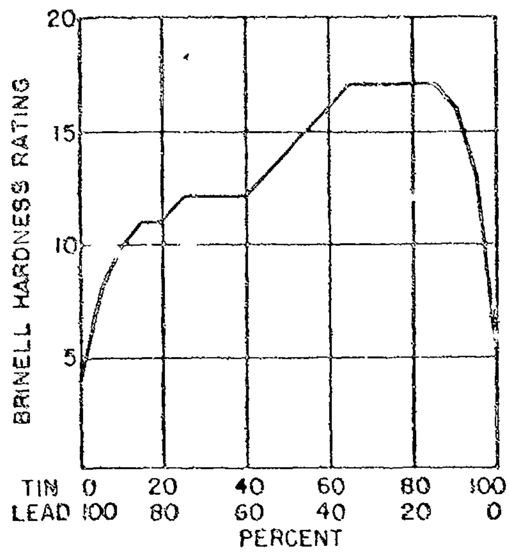


Fig. 5-9. Variation in hardness with tin content.

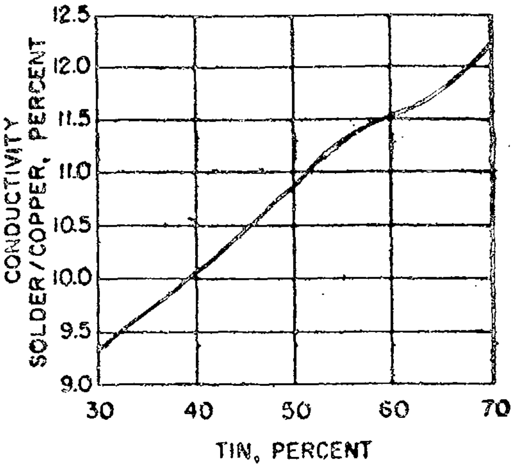


Fig. 5-10. Conductivity as a function of tin content.

A corrosive flux residue should be removed, not neutralized. Because the use of such fluxes is unacceptable for wiring components into electronic equipment, the reader should get specific information on their use when they cannot be avoided.

Electrolysis. When two dissimilar metals are in contact in the presence of an electrolyte, galvanic or electrochemical corrosion occurs. Essentially, a galvanic couple is formed which is short-circuited on itself through the electrolyte; the electrolyte may be moisture of any kind. The metal of higher potential will become an anode, tend to go into solution and corrode. With specific regard to solder, in time this can create decreased electrical conductivity and weakened physical condition.

Creep. Creep may be de[illegible] as the time-dependent deformation which [illegible]companies the application of a stress or combination of stresses to a solid. The stresses include tension, compression, torsion, and flexure. This undesirable quality of metals causes them to undergo a continuous deformation with time, the actual deformation being subject to variations (themselves subject to their own variation due to the nature of the specific metal) which occur generally in the following sequence:

1. An initial extension or elongation.
2. A stage of creep at a decelerating rate.
3. A stage of creep at an approximately constant rate.
4. A stage of creep at an accelerating rate leading to fracture.

Figure 5-11 illustrates the observed effects, and shows the influence on the creep of 99.9 percent pure lead caused by additions of 0.1 percent by weight of various elements.

APPLICATION NOTES

In performing soldering operations correctly, it is essential to select the proper solder and soldering iron. Soldering irons should be selected according to the physical size of the work to be soldered, the temperature characteristics of the solder used, and the rate of use on production. In general, the soldering iron should be as large as conditions of work will permit. Soldering irons should always be sufficiently large to rapidly heat the joint to the temperature required to melt solder. This prevents the surrounding materials from becoming overheated and damaged by a prolonged heating of the soldered joint. Solder meeting the requirements of QQ-S-571b, compositions Sn60, Sn50, and Sb5, should be used on Air Force Electronic Equipments.

All work to be soldered should be clean and free from excessive oxides or foreign materials. This will permit the flux to remove any small amount of oxide present and the solder to flow freely. Neutral fluxes, according to Specification MIL-S-6872, should be used when soldering electrical connections in electronic equipments.

Electrical connections should be mechanically secure before the soldering operation is performed. To avoid cold joints, the work should be rigid and should not be moved until the solder has cooled.

In performing solder operations, the heat should be applied to the surface to be soldered. Apply sufficient heat to melt the solder, then apply enough solder to neatly cover the connection. Avoid using excessive solder since this increases cost, and sometimes results in short circuiting adjacent terminals. Solder should never be melted on the iron and flowed to the terminals or wires. This will result in an imperfect connection.

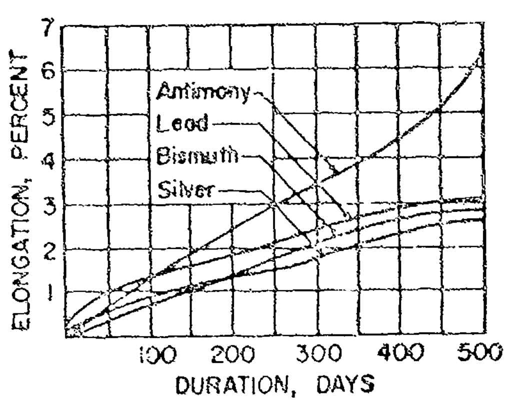


Fig. 5-11. Creep curves of lead alloys with 0.1 percent added element. Stress, 350 psi.

Solder Iron Tip Materials

For optimum efficiency a soldering iron tip should possess characteristics of high thermal conductivity, low scaling at elevated temperatures, ease of tinning, resistance to tin amalgamation, and hardness. Copper or copper alloys are most frequently used.

Copper soldering iron tips have high heat conduction and good tinning properties which make them suitable for most intermittent soldering applications. The disadvantages of using plain copper lie inherently in its scaling and rapid tip wear. The melted tin in the solder alloys with the copper at soldering temperature and carries away the tip material. Frequent scale removal, cleaning, and tinning are necessary to maintain the original tip shape and to obtain proper heat transfer from the heater element to the working surface of the tip, as well as from the tip to the joint. A well tinned tip provides a completely metallic path to give low resistance for heat flow to the joint. A tip covered with scale, on the other hand, has about 100 times the resistance to heat flow.

Copper alloys provide better performance than plain copper. The superiority is evident in reduced scaling, increased hardness, and a longer permissible interval between tip dressings. Operation temperatures for copper alloys should not exceed 725 F to prevent destroying the low scaling and hardness properties. Some irons commercially available are provided with thermal switches to limit the temperature rise during idle time of continuous duty irons. The switches are usually located in that portion of the rest stand having intimate contact with the tip.

Tip Shape. The shape and size of a soldering iron tip required for a specific job depends on the conditions that exist in the joints to be soldered, such as lug size, the number of wires in the joint, the diameter of the wires, the required solder speed, and the solder joint clearance restrictions. A large tip surface area is necessary for fast and adequate heat transfer. The preferred tip for lug and wire soldering is the chisel type. The

most common contributory causes of rosin joint defects are the use of improper tip shapes and the wrong positioning of solder and tips on joints being soldered. The working surfaces of the solder tips should be kept clean and well tinned. Dry tips scale rapidly and will slow down heat transfer to the solder joints. To acquire proper fluxing of the solder joints, rosin core solders should be applied to the hot metals in the joint. Melting the solder on the tip and carrying it to the joint destroys the flux and results in defective connections. Iron-plated or clad tips are recommended for continuous soldering operations where differences in solder tip lengths cannot be tolerated. [illegible]er solder applied to coat the soldering iron tip greatly increases its life. Subsequent soft soldering will be performed at temperatures below the melting point of the silver solder.

Heat Requirements. High-speed soldering requires a maximum solder joint temperature of 600 F, which is slightly below the melting temperature of cadmium plating and does not destroy the solder flux activity. The minimum temperature of a solder joint should be 100 to 150 F above the melting temperature of the solder alloy. The average maximum joint temperature is approximately 550 F. Recommended average solder tip temperatures are 700 to 750 F for fast and continuous soldering operations.

Prolonged idle soldering temperatures above 750 F will cause excessive scaling in the iron core, tip freezing, short element life, carbonization of rosin fluxes, and problems in keeping tips tinned.

Use of the Soldering Iron

Proper use of a soldering iron, with adequate attention to simple details and required conditions, will produce good solder joints consistently. The following requirements are to be observed: (5)

1. The soldering iron should be used at its rated voltage.

2. Proper warm-up time, depending on iron size, must be observed.

3. The soldering iron should have a tinned tip carrying a bright smooth layer of solder on the tip surface for most effective heat transfer to the joint. If the tip does not tin with solder and flux, cool the iron and file the tip to remove surface corrosion. Immediately after cleaning, the iron should be fluxed, heated, and tinned with solder. Increased tip life with excellent heat transfer is possible by cleaning the tip and tinning with a good grade of silver solder. A solder pot is most effective for this purpose. The higher melting point of this alloy assures that the solder deposited on the tip will not be melted off during subsequent soldering operations at the reduced temperatures utilized in soft soldering.

4. All elements of the joint to be soldered must be clean. Clean metal-to-metal contact is necessary without an intervening layer of dirt, oxide film, or foreign matter.

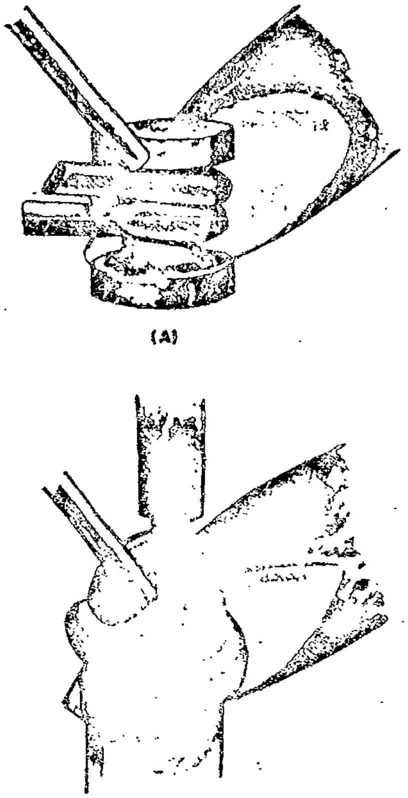
5. The parts to be soldered must be held together firmly.

6. Apply flux to the joint to cleanse the metallic surfaces down to the bare metal and to exclude air during the soldering operation. Select the proper flux for the application. Rosin-type fluxes are mild and leave harmless residues. Acid-type fluxes are stronger and leave corrosive residues which also conduct electric current and must be washed off to preserve the electrical and physical stability of the joint. Certain materials such as aluminum and stainless steel require special fluxing techniques.

7. Heat the joint with the hot tip of the iron and apply solder to the junction of the tip and joint as shown in Fig. 5-12. As soon as the soldering temperature is reached (solder wets the joint surfaces and flows smoothly), remove the iron from the joint. Avoid excessive use of solder. The joint must not be jarred or subjected to vibration while the molten solder is cooling and solidifying. Such motion can cause a cold solder joint which is physically characterized by a dull gritty appearance, poor joint strength, and low electrical conductivity. (See Figs. 5-13, 5-14, and 5-15.)

8. Where possible, pretinning of individual parts is recommended to obtain quicker soldering and more reliable solder joints.

9. The soldering iron must be properly maintained during use. A clean cloth or wiping pad used at intervals will remove excess solder and slag which speed erosion of the tip. When not in actual soldering use, a soldering iron should be rested on a stand which has adequate heat dissipating area. This stand provides a controlling factor over the idle temperature of the iron, and helps to avoid the ill effects on the iron caused by overheating.



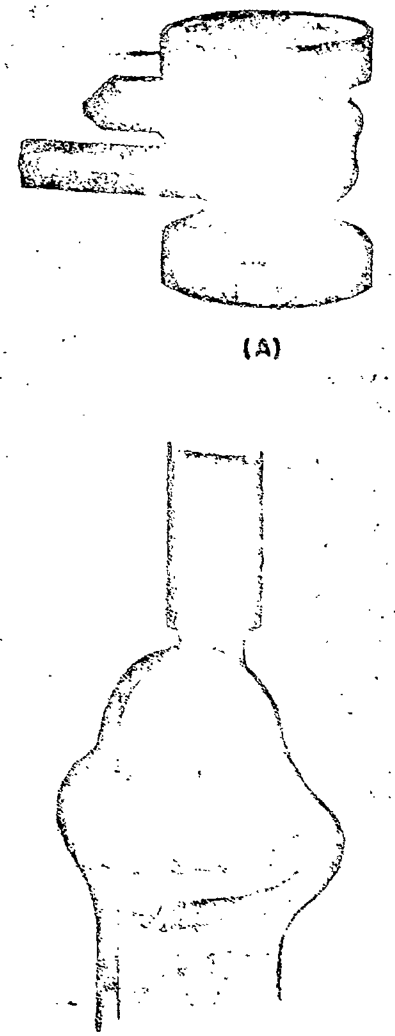
(A)

(B)

Fig. 5-12. Application of solder and iron to lugs.

Inspection

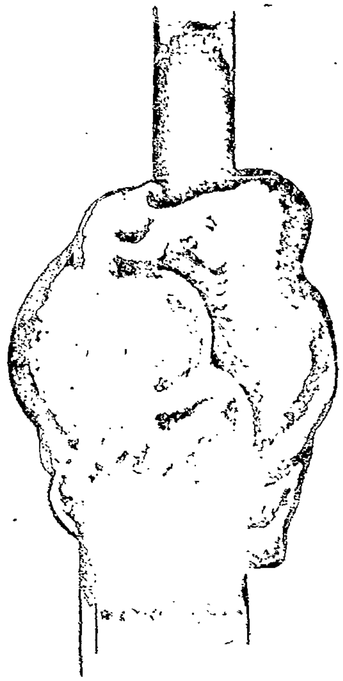
A properly made solder joint has a smooth appearance with a satin-like luster. A wire which is soldered as part of such a joint will be rigid in the immediate vicinity of the joint. Wiggling the wire by hand or with small pliers will reveal whether or not this rigidity is present. Visual inspection of the joint will reveal if the joint has the required physical appearance. Departure from the desired condition on any one of these points may indicate that a "cold joint" has been created. This may mean that all the surface areas of the solder joint were not brought up to the temperature required for solvent action to take place. Frequently this type of defective joint results from accidental relative movement of the components being soldered during the solder cooling interval, that is, while the solder is changing from a liquid to a solid state. Correction requires unsoldering and disassembling the joint, cleaning all surfaces which are to form the joint, and resoldering, observing good craftsmanship in all phases of the operation. Only careful supervision will make certain that these steps are carried out. The average operator will merely reapply the iron in the hope that the joint will be secured.



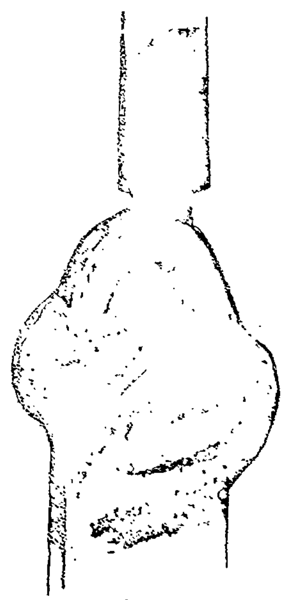
(A)

(B)

Fig. 5-13. Acceptable solder joints.



(A)



(B)

Fig. 5-14. Unacceptable solder joints: (A) Excessive solder, (B) Rosin joint.

EFFECTS OF ENVIRONMENT ON SOLDER

The following environmental data are included to provide the design engineer with an evaluation of the metallurgical characteristics of solder alloys, and the behavior of these metals under atmospheric conditions and stresses.

This information specifically concerns soft solders as covered by Federal Specification QQ-S-571b. This group of solder alloys has the widest application in the assembly of electronic equipment and components. Effects of temperature, aging, moisture, vibration, and fungus attack are considered. The following solders representative of this group were evaluated: (4)

70Sn-30Pb	20Sn-80Pb
50Sn-50Pb	2.5Ag-97.5Pb
35Sn-65Pb	5Sb-95Sn

Effect of Temperature on Tensile Strength

The effects of aging solder joints at various temperatures for periods of six months or more are given in Table 5-8. Aging solder joints at reduced temperatures has the general effect of increasing the joint tensile strength, the increase in strength being greatest in the high tin-lead solders. A small but tangible increase occurred in the lead-silver solders because lead remains ductile at low temperatures. Solder joints lose strength progressively with increase in temperature. At 212 F, most solders lose about 50 percent of their strength, while at 300 F only about one-third the room-temperature strength remains. From the above figures the most suitable solder for the temperatures considered is the 70Sn-30Pb solder. It shows superior strength at high, low, and intermediate temperatures, and is the easiest solder of the group to use.

Effect of Aging on the Strength of Solders

Four solders were subjected to six-month aging periods at the static temperature levels of -65 C (-85 F), 25 C (77 F), 75 C (167 F), and 120 C (248 F). Following this aging period, half the specimens were permitted to return to room temperature. When aged and tested at -65 C (-85 F), all solders showed an increase in joint strength (see Table 5-9) except the 20Sn-80Pb specimen. After aging at the reduced temperature, all solders were weaker at room temperature except the 50 Sn-50Sb. Aging at 75 C (167 F) weakens all solders tested. After aging at 75 C (167 F)

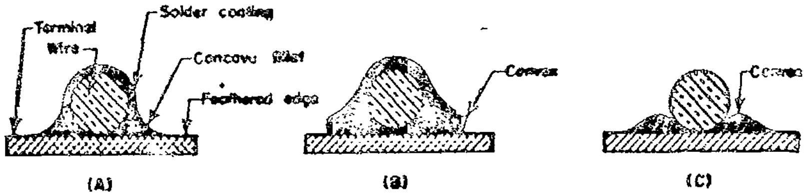


Fig. 5-15. Examples of a good joint (A) and bad joints (B and C).

and then returning to room temperature, 50Sn-50Sb and 95Sn-5Sb were stronger, while the 70Sn-30Pb and 20Sn-80Pb solders were weaker. At 120 C (248 F) aging had no influence except on the 95Sn-5Pb solder which was weakened. After aging at the high temperature, each solder was stronger than before aging. From this investigation it appears that the 50Sn-50Pb solder is the least affected by thermal variation.

Effects of Temperature Cycling on Tensile Strength

To determine the effects caused by combined thermal shock and possible corrosion, four solders were cycled between -65 C (-85 F), 30 C (86 F) with high humidity, and 120 C (248 F). Three cycles, approximately 3.5 weeks under each environment, were initiated and the solders were allowed to return to room temperature. Little change was noted in the strength of the joints due to cycling in temperature from what might have resulted from aging at the same temperature for the same time interval. The only substantial sign of change occurred in the 50Sn-50Pb solder; this solder may weaken under varying conditions of use.

High Humidity and Fungus Growth Tests

After about 5.5 months exposure to a tropical environment and exposure to microbiological culture media, tensile-type specimens were withdrawn for test and were evaluated. (4) A coating of solder flux was left on certain solder joint surfaces; other joints were dissolved of flux residue and wiped clean.

Examination disclosed that the residual solder flux did not act as a good source of fungus nutrients. However, the flux residue did act as a particularly good base for fungus growth if the nutrients were supplied from outside. The results showed that while all the soldered joints were weaker than at the start of the tests, they were not significantly different from joints aged under ordinary room temperature conditions.

Vibration

Fatigue tests were undertaken at three different temperatures to determine the behavior of the soldered joints under vibratory stresses. These were conducted on Krouse direct-stress fatigue machines at 1500 cycles per minute. The maximum stress for each solder was approximately one-half the mean ultimate strength at test temperatures. A minimum stress of 100 pounds was used to ensure continuous tension conditions during test. The results, while unclassifiable from many aspects, did show a trend which can be expected from other joints made with the same solders and subjected to a vibrating load. The

Table 5-8—Effect of Temperature on Tensile Strength of Soldered Joints.

Solder composition	Breaking load (lb)				
	-65 C* (-85 F)	-20 C* (-4 F)	+25 C* (+77 F)	+75 C* (+167 F)	+120 C* (+248 F)
70Sn-30Pb	3670	3041	2130	1730	1150
50Sn-50Pb	2790	2553	1690	1260	910
35Sn-65Pb	2490	—	1675	—	900
20Sn-80Pb	2190	2050	1420	1310	1010
2.5Ag-97.5Pb	1490	—	1130	—	530
95Sn-5Sb	3130	2360	2090	1420	1100

* Temperature of test.

Table 5-9—Tensile Strength Data on Soldered Joints Aged for Six Months at Four Temperatures

Solder composition	Breaking load (lb)			
	-65 C* (-85 F)	+25 C* (+77 F)	+85 C* (+187 F)	+120 C* (+248 F)
Tested at aging temperature				
70Sn-30Pb	4300	1765	1860	1115
50Sn-50Pb	4050	1490	1690	925
20Sn-80Pb	1980	965	785	680
95Sn-5Pb	2580	1830	1610	930
Tested at room temperature				
70Sn-30Pb	2070	—	1619	1430
50Sn-50Pb	1600	—	1330	1450
20Sn-80Pb	1263	—	1010	1170
95Sn-5Pb	1720	—	1540	1345

* Aging temperature.

maximum load encountered was 1500 pounds. Since this is near the tensile strength limitation of 20Sn-80Pb solder, this alloy showed very short fatigue life. Joints having higher tensile strength had longer fatigue life. The 70Sn-30Pb and 95Sn-5Sb were equal in tension, but the fatigue life of the 70Sn-30Pb is much greater. The 50Sn-50Pb solder which was much weaker than the Sn-Sb solder in tension is equal to it in fatigue life. This indicates that, at normal temperatures, the Sn-Sb solder would be a poor choice for use under vibrating loads. No outstanding reaction was noted from any one solder which might induce the design engineer to favor or reject it for fatigue resistance behavior at 120 C (248 F) beyond the recommendation that the 20Sn-80Pb solder should not be used where the vibration environment is rendered more critical by elevated temperatures.

PRINTED CIRCUIT SOLDERING

Reliable printed circuit solder joints of uniformly high quality are produced by following carefully controlled steps, each of which has its own unique importance.

Since etched copper wiring boards do not solder as readily as plated boards, it is common practice to electroplate the bare copper areas with deposits of cadmium, silver, or gold, or more frequently with tin alloyed with lead, zinc, copper, or nickel. (4) Hot tinning is also used to improve solderability. Plated boards have superior physical characteristics since they possess better initial solderability and better storage characteristics.

The wiring boards used in this assembly technique are often stored for arbitrary periods before being used. To keep solderable surfaces free from contamination, and prevent the formation of oxide film on the metallic areas, protective coatings are applied which consist basically of wax, water dip lacquers, and even solder fluxes. Also, inorganic materials, such as chromates, will form protective films over the metallic surfaces to be preserved. This treatment minimizes the formation of oxide or sulfide film and keeps the metallic surfaces in prime condition for soldering. It prevents contamination from perspiration or from fingerprints and also avoids etching by a variety of organic corrosives.

Bath Mixture. The most practical and workable bath mixture for dip soldering of copper-etched as well as plated boards is 60 to 63 percent tin, with lead making up the remainder. The eutectic composition of 63 percent tin and 37 percent lead offers the slight advantage of a liquidus temperature approximately 9 degrees lower, with moderately superior spreading characteristics.

Bath Temperature. Recommended dip-soldering temperatures are 460 to 470 F. Temperatures of 450 to 550 F are actually in use, but the comparative merits and safety of this practice depend on attendant factors, such as the size of the wiring board and the number of components which may be jeopardized by exposure to heat from the solder bath.

Bath Size. The quantity of the bath material must be great enough to prevent a reduction in temperature when the assembly is dipped. This is especially important at the low temperature used in dip soldering printed wiring boards.

Dwell Time. Dwell time in the solder bath for 60/40 or 63/37 tin-lead solders will generally vary between three and eight seconds, depending on the size of the board and the number of components being soldered. The wiring board or assembly to be dip soldered should be immersed in the solder bath gradually and withdrawn in the same manner.

Bath Agitation and Replenishment. The contents of the solder bath should be agitated at least once each day, preferably after the solder pot is initially heated. Since soldering is alloying, that is, the diffusion of metals into one another, a buildup of impurities from components being dipped into the pot is inevitable, and eventually the contaminated contents of the pot must be discarded and a fresh start made. The slow addition of copper to the solder bath gradually raises the melting point

of the solder mixture to a point where the heating unit can no longer maintain the mixture in the liquid state. This phenomenon occurs because the tin-copper crystallization leaves the mixture deficient in tin. Replenishment with pure tin is necessary to maintain the mixture at the desired ratio of tin to other alloy elements. Figure 5-16 shows the trace impurities found in a production-line solder pot by spectrographic analysis at the indicated intervals.

Dip-Soldered Joint Testing

Considerable effort was expended by the Eastman Kodak Company upon a program investigating dip-soldered joints from the standpoint of results which can be anticipated in production. (6) This program covered four fields:

1. Efficiency of joint formation.
2. Short-time tensile strength.
3. Impact strength in tension.
4. Creep strength in tension.

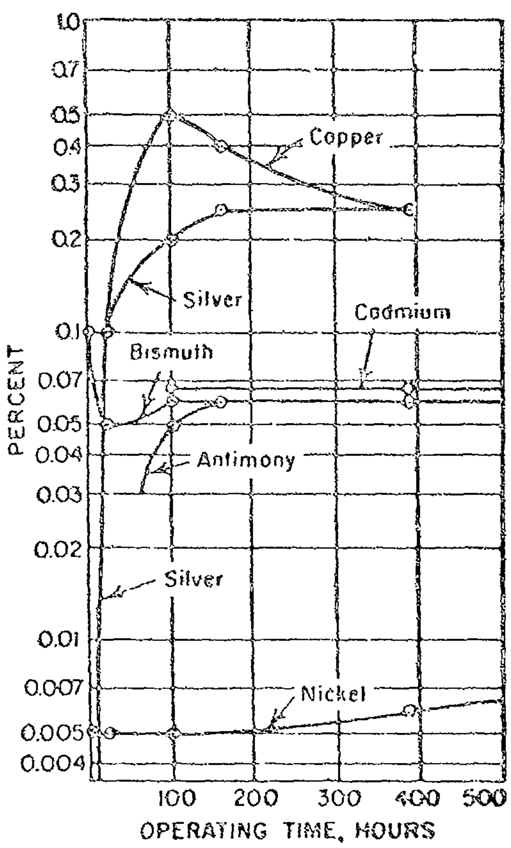


Fig. 5-16. Dip-solder pot trace impurities.

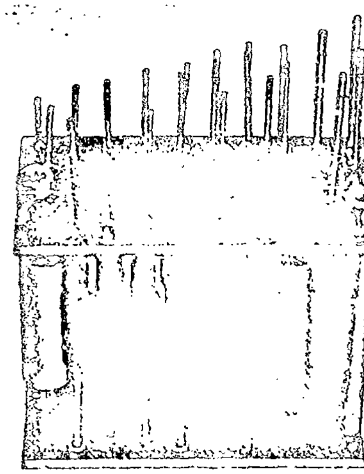


Fig. 5-17. Dip-soldered bundle. (Eastman Kodak Company.)

The dip-soldered joints used for evaluation were made in the form of bundles using obsolete production photo-etched boards as shown in Fig. 5-17. A typical bundle and distribution deck is shown in Fig. 5-18. A cross-sectional view of a typical bundle is shown in Fig. 5-19. This type of straight-through joint tested is not generally in use. The majority of joints employ a crimp or clinch to mechanically secure the connection.

All the dip-soldered joints were tested at 70 F except one type discussed later. The tests were made using a 5-second dip in 60 percent tin 40 percent lead solder at a temperature of 550 F. Activated rosin flux was used throughout.

All strength tests were made using single joints from the test bundles. The preparation of these samples was standardized to minimize variables. The test samples consisted of a series of dip-soldered joints and 1-inch

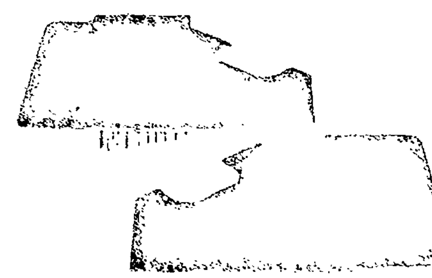


Fig. 5-18. Bundle and distribution deck.

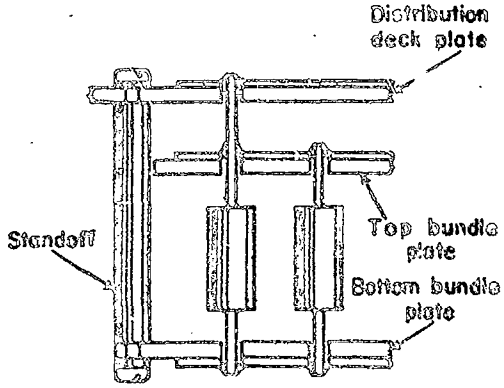


Fig. 5-19. Cross-sectional view of bundle.

leads with steel washers attached as shown in Fig. 5-20.

Failures. Failures were of two types: those which occurred in the dip-soldered joint, and those in which the wire lead failed (see Fig. 5-21). Since the purpose of the program was to determine the overall joint strengths which can be achieved in production, it was assumed that a wire lead failure indicated that the dip-soldered joint associated with that lead is stronger than the lead itself. Therefore, with the exception of impact test results, lead failures and joint failures are averaged.

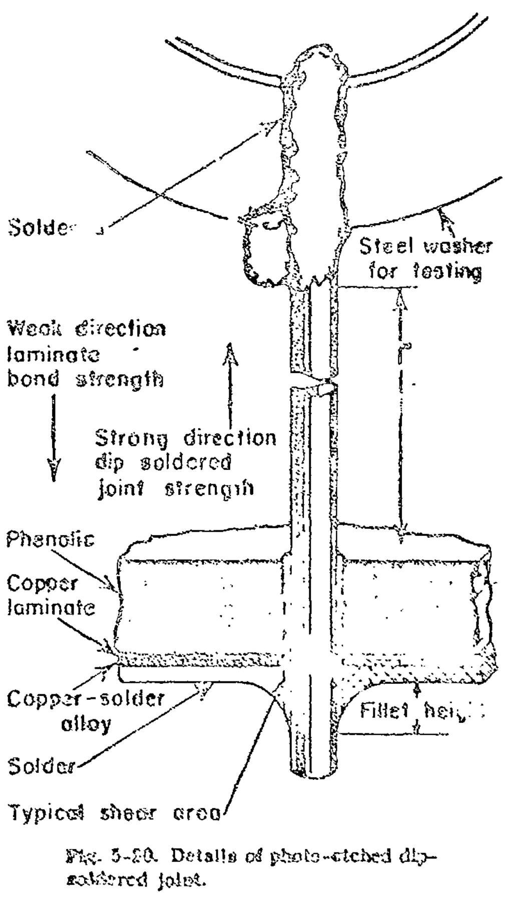


Fig. 5-20. Details of photo-etched dip-soldered joint.

Efficiency of Joint Formation. In evaluating the efficiency of dip-soldered joint formation, defective joints are considered to consist of two types. Since no official or formal identifying names have been given to these types, they are currently termed "misses" and "partials." Misses are those joints that have no solder continuity between the lead wire and the photo-etched pattern. Partials are dip-soldered joints in which the solder fillet is incomplete. The combined types are shown in Fig. 5-22 which illustrates that with 0.010-inch diametral clearance, efficiencies of 98 to 99.2 percent can be expected. Diametral clearances over 0.010 inch result in substantial reduction in efficiency. The efficiency curve is the result of visual inspection of an average of 650 dip-soldered joints for each diametral clearance. A more detailed analysis of the test data shows that for a given diametral clearance, smaller wires tend to be more efficient in joint formation. Detailed production records show that from 15 to 20 percent of all defective joints were misses. These records further show that of 50,000 joints observed, 0.25 percent were misses and 1.19 percent were partials. The balance of the joints (98.56 percent) were satisfactory.

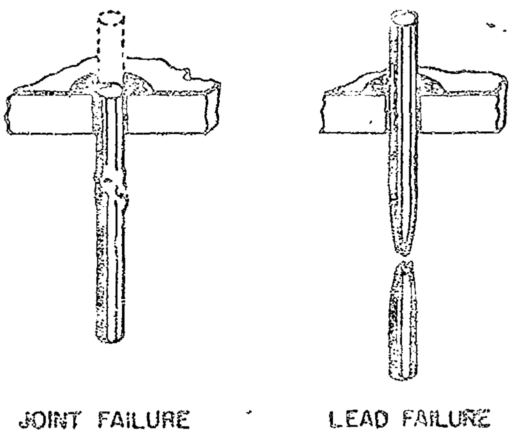


Fig. 5-21. Joint-lead failure details.

Poor joints may be formed when dirt or oxides are present on the surface of the

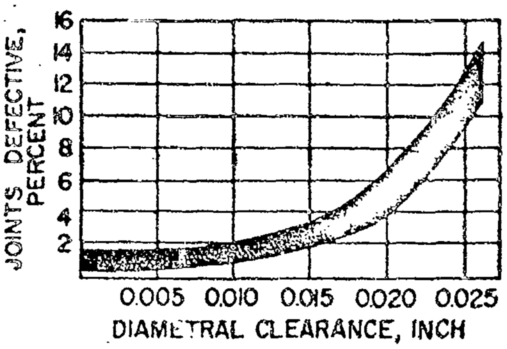


Fig. 5-22. Effect of diametral clearance on joint defects.

leads. The oxides are assumed to be the result of porous plating which allows either copper oxides or sulfides to migrate through to the surface and prevent acceptable fillet formation. Several methods of cleaning assemble' components, leads, and boards immediately prior to fluxing are now being considered as a method of further increasing the efficiency of dip-soldered joint formation.

Short-Time Tensile Strength. The short-time tensile tests were made on a Baldwin Southwark Universal testing machine with a Tate Emery air cell to reduce the normal 24,000 pound capacity to a range of 0 to 240 pounds. The speed of the movable head was 1 inch per minute.

The results of short-time tensile tests are shown in Fig. 5-23 and Table 5-10. In general, there is a tendency for joint strength to be mainly a function of wire size, and to be relatively independent of diametral clearance. Smaller wires seem to have more constant strength in relation to diametral clearance because, beginning with AWG No. 22, lead failures make up an increasing part of total failures.

Impact Strength in Tension. Evaluating dip-soldered joints for impact strength in tension required the development of a testing machine. The machine is similar to standard impact machines in that it measures the energy required to cause fracture. In making a measurement, the pendulum is dropped from a specific angle, and the follow-through angle is measured. The difference between the initial energy and the follow-through energy is the energy required to cause fracture.

As part of the calibration process, a stress-strain diagram was plotted for No. 20 copper wire, and the theoretical energy required for fracture was calculated. Results of these impact tests of this same wire checked so closely that the impact index is considered a true energy value.

The average and range of values of impact strength in tension of 100 samples for each wire have been obtained. Detailed results show that impact strength is independent of

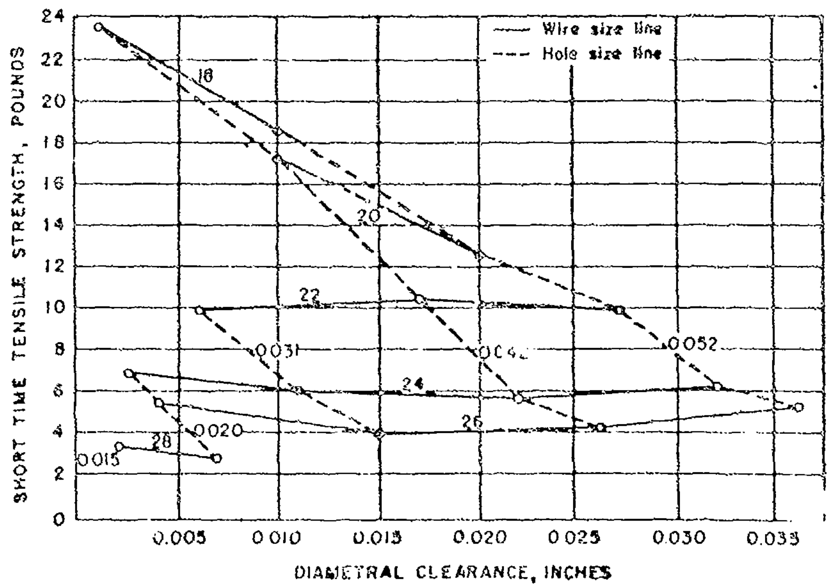


Fig. 5-23. Short-time tensile strength of photo-etched dip-soldered joints.

Table 5-10—Standard Dip-Soldered Joints, Average Strength for 0.010-inch Diametral Clearance, Copper Wire

Short-time tensile strength*			Impact in tension*			
Wire AWG	Strength (lb)	Joint failure† (%)	Impact index‡ Joint	Impact index‡ Lead	Joint failure† (%)	Average impact index¶
16	29.8	100	0.5-4.0	--	100	2.1
18	18.6	100	0.5-5.0	--	100	2.4
20	17.2	100	0.5-4.5	6.5-8.0	72	3.5
22	[illegible]	100	0.5-3.5	3.0-5.0	66	2.3
24	6.1	92	0.5-3.5	1.5-3.5	61	2.3
26	4.6	58	0.5-1.0	0.5-1.0	18	0.9
28	2.5	15	--	--	--	--

* Average number of samples tested: short-time tensile strength, 26; impact in tension, 100.

† This figure represents that portion of the total dip-soldered joints tested which failed in the joint. The remaining failures occurred in the lead.

‡ This figure represents impact strength compared to that of No. 20 copper wire.

¶ This figure represents a statistical average of both joint and lead failures.

diametral clearance. Therefore, the results shown in Table 5-10 and Fig. 5-24 are presented as a function of wire size only. The resulting impact index is directly proportional to wire diameter. Inconsistencies in the averages are due to wire annealing, elasticity, and other test sample variables which cannot be completely controlled but would be encountered in regular production.

Creep Strength in Tension. The creep strength of solder is often considered its poorest characteristic since a joint may fail under a relatively small continuous load. To evaluate creep strength, samples were tested by suspending fixed weights on dip-soldered joint samples until fracture occurred. The fillet heights of individual joints were measured before the samples failed. The strength results were directly related to these fillet heights. Figure 5-25 shows the relationship of the applied load and time required for failure to be a logarithmic function.

The significance of creep strength is more evident in cases where the relief of internal stress might cause fracture. This condition can be largely eliminated in design by pro-

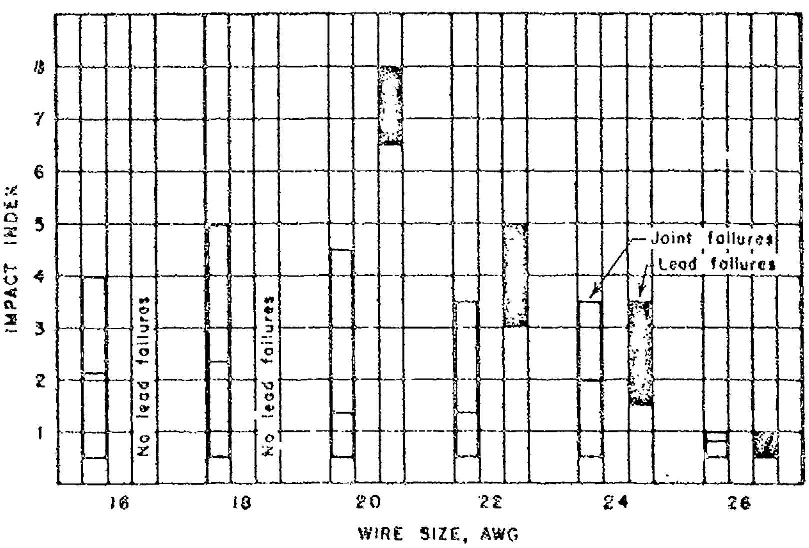


Fig. 5-24. Impact strength in tension of photo-etched dip-soldered joints.

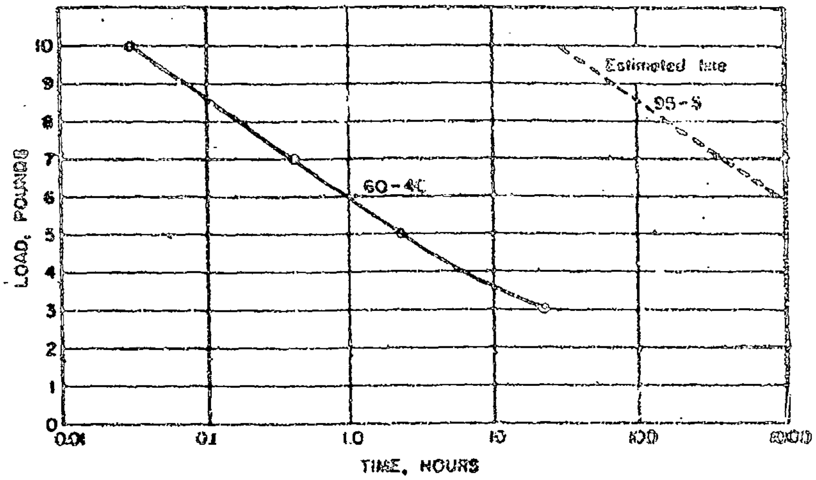


Fig. 5-26. Creep strength in tension of photo-etched dip-soldered joints.

viding rigid mountings or numerous components between the photo-etched boards.

Dip-soldered Joint Strengthening. Since the strength of a dip-soldered joint is essentially the shear strength of the solder in the fillet, the method for increasing strength is to increase the fillet height. Figure 5-26 shows the relation of dip-soldered joint fillet height to short-time tensile strength. Photo-etched conductor pattern design is also a factor in the formation of large symmetrical dip-soldered joint fillets. No effort was made to take pattern design into consideration in evaluating methods of joint strengthening. The following methods of joint strengthening have been tried with and without success:

1. Notching, crimping, bending, flattening, flaring, or otherwise altering that portion of the wire which is included in the solder fillet (see Fig. 5-27).
2. Using eyelets or plated-through holes.
3. Using another material on the back of the board around the leads.
4. Controlling the length of the lead which is dipped into the solder.

Of the methods listed in (1) above, flaring of a portion of the lead which is included in the solder fillet is the only method which shows a significant strength increase (43 percent). Flaring is accomplished with a tool which cuts and flattens the wire so its greater dimension exceeds the hole diameter in the board. In this way, not only the shear strength of the solder, but also the interference of the flattened portion of the wire with the photo-etched board contributes to the overall joint strength. This method is effective only for leads which can be cut off prior to dipping.

The eyelet joints tested used individual brass eyelets staked into holes in the printed board. In using unplated or thinly plated brass eyelets it is likely that solder pot contamination with zinc will result. Tests of joints in which the inside surface of the hole was covered with plating showed that failure often occurs in separation of the plating from the hole surface. In plated-through joints, there is a significant tendency for voids to form in the solder filling the hole. The strength of both eyeletted and plated-through joints compared in Tables 5-11 and 5-12 is greater than that of AWG No. 20 wire. Since the components in general use have AWG No. 21 or smaller leads, it is believed there are other methods of joint strengthening which are adequate and do not involve the extra expense for eyelet assembly or plated-through holes.

By applying shellac or epoxy resins around the leads on the back of the photo-etched board after dip soldering, it is possible to increase the overall joint strength. Since epoxy resins are insoluble after curing, repair is not practical. Shellac, however, is readily soluble in alcohol, and units on which it is used are repairable. Although epoxy resin joints are stronger than shellac joints, the shellac is 18 percent stronger than standard joints, this making it satisfactory for joint strengthening without the necessity of an additional operation. It is felt that shellac application should be considered first.

In the course of dipping experimental bundles, it was reported that when leads dipped

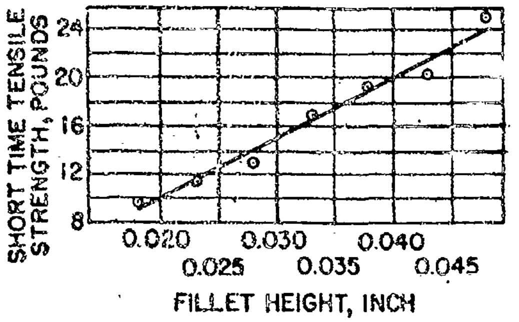


Fig. 5-26. Relation of fillet height to short-time tensile strength.

into the solder were short, the solder fillets appeared to be larger. (6) Specific tests proved that when leads are 1/8 inch long, the increase in solder fillet height is greatest. This is probably due to the fact that the whole lead is removed from the solder pot before all excess solder can run off. The remaining solder then becomes part of the solder fillet. Comparison with standard dip-soldered joint fillet heights show that 1/8-inch leads result in a 30-percent height increase and a 35-percent short-time tensile strength increase over corresponding average values for standard joints. This method of joint strengthening is applicable only to leads which are not used for connections to adjacent units.

A solder containing 95 percent tin and 5 percent antimony was recommended for this particular dip soldering application since all available test information indicates that it has considerably more strength in all categories than the 60 percent tin and 40 percent lead solder. However, insufficient tests have been made to show that this composition is better than eutectic solders. Initial experiments showed acceptable results when used on photo-etched boards with 0.080 inch or more between conductors. Close conductor spacing (0.020 to 0.040 inch) allowed a slight amount of bridging between patterns. Further investigation showed that the lead in the 60/40 solder plated on the conductors apparently contaminated the tin-antimony solder, and was responsible for the bridging. Bare copper conductors dipped in 95/5 tin-antimony solder gave results which surpassed those of 60/40 tin-lead solder.

The tin-antimony composition lacks a sharp eutectic point, and exhibits a plastic range of approximately 18 F (10 C) through which the solder must pass before complete solidification takes place. The liquidus point is approximately 460 F which is 100 F above that of 60/40 solder. Dipping gives satisfactory results. Joint efficiency has been measured only in laboratory experiments; however, it seems superior to that of 60/40 solder. Of 754 joints dipped in 95/5 solder, there was only one imperfect joint formed or 0.133 percent defective as compared with the average of approximately 1 percent defective obtained with 60/40 solder and a similar wire size. It forms fillets which average 25 percent greater in height. It also builds up on metallic fixtures faster than 60/40 solder. Measurements of strength show that 95/5 solder joints are 30 percent stronger in tension, 63 percent stronger in impact, and 750 to 950 times as strong as 60/40 solder joints in creep. These results verify the predictions made for this material.

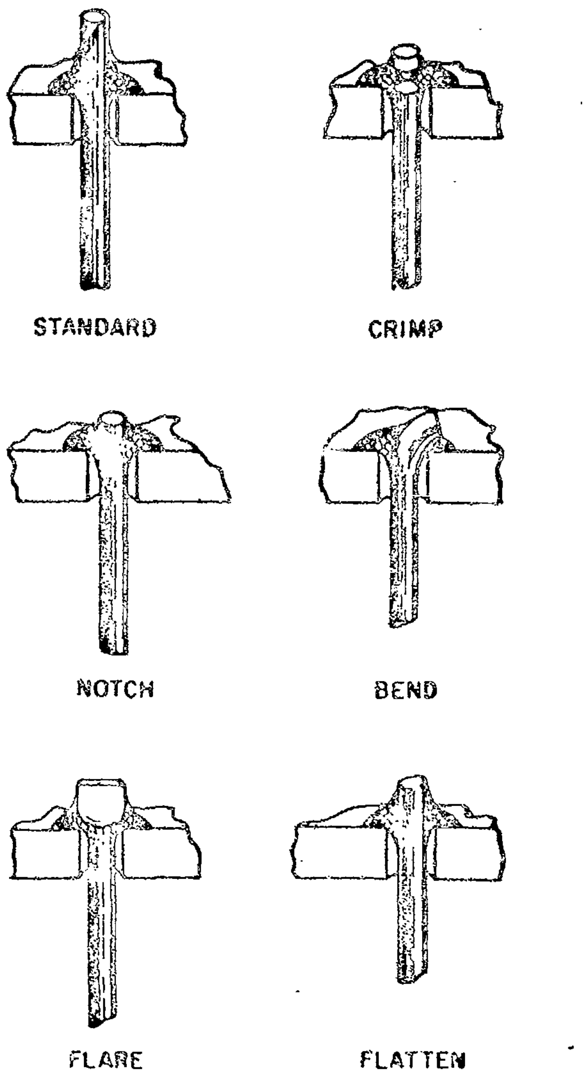


Fig. 5-27. Conductor preparation to improve joint strength.

Table 5-11—Relative Joint Strengths

Description	Short-time tensile strength					Impact in tension strength			
	Figure No.	Strength (lb)	Joint failure* (%)	Sample size	Increase over standard joint (%)	Impact index	Joint failure* (%)	Sample size	Increase over standard joint (%)
No. 20 Wire, 0.042-in. hole, flared lead	13	24.7	58	48	44	--	--	--	--
No. 20 Wire, 0.048-in. hole, brass eyelet	14	30.5	0	45	112	--	--	--	--
No. 20 Wire, 0.062-in. hole, plated-through hole	14	26.0	30†	24	124	6.7	4†	23	92
No. 20 Wire, 0.042-in. hole, epoxy resin on back of board	15	25.6	82	17	49	6.7	28	40	91
No. 20 Wire, 0.042-in. hole, shellac on back of board	15	20.4	100	19	19	7.5	7	15	114
No. 20 Wire, 0.042-in. hole, leads 1/8 in. long before dipping	15	23.3	55	18	36	5.0	56	25	43
No. 20 Wire, 0.042-in. hole, 95-5 solder (Std)	13	33.4	95	44	30	6.9	20	73	97
No. 20 Wire, 0.042-in. hole, 95-5 solder, leads 1/8 in. long before dipping	15	24.4	85	48	42	6.9	10	47	97

* This figure represents that portion of the total dip-soldered joints tested which failed in the joint. The remaining failures occurred in the lead.

† In these samples, joint failure consisted of the solder-filled plating in the hole separating from the phenolic board.

Tin-antimony solder of the 95/5 composition was also tested for increased fillet height and joint strength with a lead length of 1/8 inch prior to dip soldering. The increases were not as great as with 60/40 solder. Since 95/5 solder joints dipped with leads 1/2 inch long have fillet height and short-time tensile strength which are only slightly below the corresponding values for 60/40 solder joints made with leads cut to 1/8 inch, it is believed that these results do not indicate a disadvantage of 95/5 solder. Flaring leads and controlling lead length, as discussed above, are two means of joint strengthening which are not applicable when leads must be left long for connections to other units. The 95/5 solder does not have this limitation.

Double dipping is often used ineffectively as a means of increasing fillet height and joint strength. Tests show that double dips over the original joint do not serve any practical purpose, except possibly to fill any voids left from the original dip. Refluxing is necessary

Table 5-12—Wire Strength

Wire AWG	Short-time tensile strength (lb)	Impact in tension impact index
No. 20 Copper	26.4	7.7
No. 22 Copper	16.1	3.9
No. 24 Copper	9.4	2.8
No. 26 Copper	4.9	0.9
No. 28 Copper	3.25	--
No. 22 Steel	37.5	6.8
No. 24 Steel	17.2	3.1
No 25 Steel	11.4	3.3
No. 26 Steel	13 0	1.7

for acceptable solder flow. The second dip melts the first fillet, but does not increase the final fillet size. It is believed that it tends to disperse the copper-tin alloy plane with a corresponding joint strength decrease. This is not true if some change is made in the mechanical configuration between dips. Flare-cutting the leads would be an example of such mechanical change.

Conductor Patterns. The design of photo-etched conductor patterns has a vital influence on dip-soldered joint efficiency. Two generalizations concerning design specifications of these patterns may be drawn.

1. Teardrop or streamlined design with no sharp angles or coners is preferred. Careful attention should be given to avoid pattern configurations which give poor results as shown in Fig. 5-28. Some of these poor conductor patterns cause defective joints while others result in small or nonsymmetrical dip-soldered joint fillets.

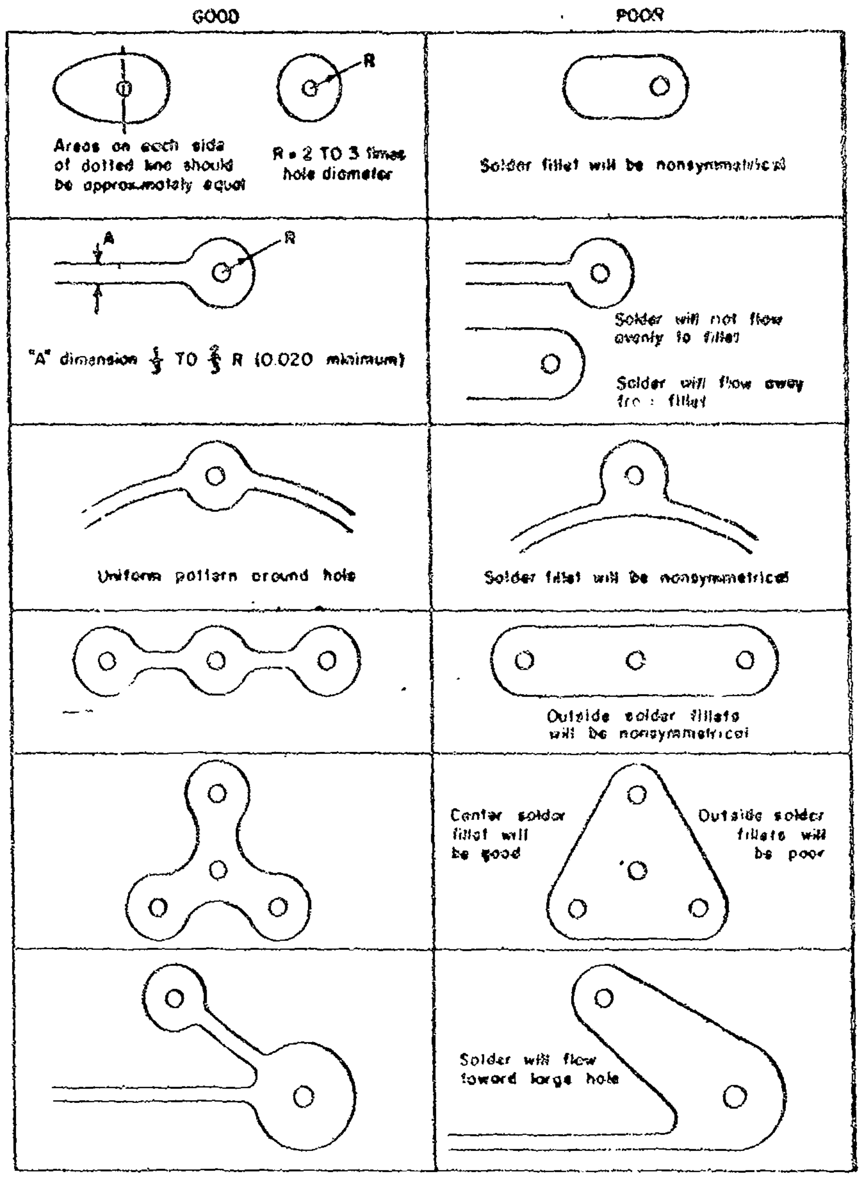


Fig. 5-28. Photo-etched conductor patterns.

2. To avoid process problems, the suggested minimum conductor pattern width is specified as 0.020 inch, and the minimum clearance between conductors as 0.020 inch at any one point. Whenever the space commitments permit, the minimum clearance should be increased to 0.040 inch, and the conductors should be designed so that they do not run parallel to each other for a greater distance than necessary.

DO'S AND DON'T'S FOR SOLDERING

1. Do not solder unclean or oxidized surfaces.
2. Use only rosin fluxes.
3. Do not depend on a soldered joint to withstand mechanical or physical stress.
4. When soldering zinc or galvanized iron, use a solder composition with little or no antimony.
5. In dip-soldering, always use a solder pot or bath wide enough to accommodate work pieces comfortably, and deep enough to maintain uniform temperature.
6. Avoid prolonged immersion of work pieces in a solder pot to reduce solder pot contamination. This condition is to be avoided as it raises the melting point of the solder mixture.
7. Avoid double dipping printed circuit assemblies.
8. Don't put terminals too close together.
9. Don't use solder to hold parts together.
10. Design equipment into subunits easily soldered.

REFERENCES

1. Tentative Specifications for Rosin Flux Cored Solder, ASTM, B 284-53T, 1953.
2. "Workmanship and Design Practices for Electronic Equipment," Ordnance Publication No. 2230, BuOrd, U. S. Navy.
3. "Properties of Soldered Joints," Circular 492, National Bureau of Standards.
4. Report of RETMA Conference on Reliability of Electrical Connections. Available from Engineering Publishers, New York, 1954.
5. Lewis, W. R., "Notes on Soldering," Tin Research Institute, Columbus, Ohio.
6. "Dip Soldering Printed Circuits and Dip-Soldered Printed Circuit Joint Characteristics," Eastman Kodak Co., Rochester, New York. Presented at Solder Symposium of the Annual Meeting of ASTM, 1956.

BIBLIOGRAPHY

Barber, C. L., "Solder—Its Fundamentals and Usage," Kester Solder Co., Chicago.

"Proceedings of Second RETMA Conference on Reliable Electrical Connections," Engineering Publishers, New York, 1956.

"Proceedings of the RETMA Symposium on Printed Circuits," Engineering Publishers, New York, 1955.

Contents

CHAPTER 6: CHOPPERS

Chapter 6

CHOPPERS*

A chopper is a high precision electromechanical device often employed in analog and digital computers, fire control systems, servo systems, or in telemetering applications. It is used where a signal to be amplified is introduced as a d-c signal or as such a low frequency a-c signal that efficient amplification is difficult. The chopper interrupts (chops) the low frequency or d-c signal at some desired rate and, in effect, converts it to a square wave signal, which can be amplified easily.

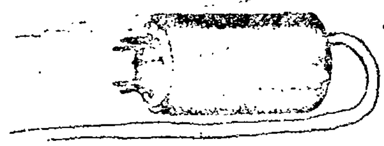


Fig. 6-1. The chopper is a completely self-contained unit. Connections may be brought out to socket pins to permit plug-in installation. Pig-tail leads frequently provide advantages in certain applications.

The chopper, as shown in Fig. 6-1, goes by other names, such as contact modulator or converter. It consists basically of a vibrating mass bearing contacts; the vibrating energy being supplied by an a-c field. In many ways the chopper resembles a relay or a vibrator; but there are significant differences in its design, construction, and application compared to these other components.

Basically, the chopper is a single-pole, double-throw switch (see Fig. 6-2), in which the movable contact is swung between two fixed contacts at a rapid and continuous rate by an electromagnetic field supplied by a driving coil through which flows alternating current at a frequency of from 15 to 1800 cps. The movable contact closes on one fixed contact for an interval referred to as the dwell time. Polarity reversal of the applied driving voltage swings the movable arm so that the movable contact closes on the other fixed contact for a corresponding dwell-time interval. The transit time is called the off time.

There is an effective phase lag between contacts and driving signal, which may be between 30 and 100 electrical degrees, depending on frequency and other factors. The lag is made up of two parts: an electrically lagging coil current and a physical lag derived from mechanical values.

The majority of choppers have a single-pole, double-throw, break-before-make contact arrangement. Most contacts have a maximum voltage rating of [illegible] volts and a maximum current rating of 4 ma at unity power factor. Construction of the chopper is such

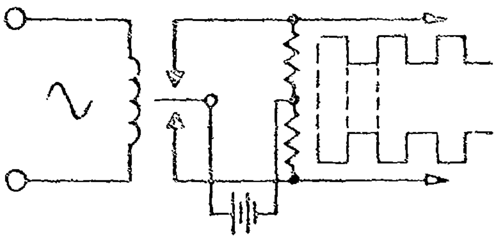


Fig. 6-2. Sinusoidal alternating current drives the chopper to make alternate contact with either of two fixed contacts.

* The editors have drawn heavily on notes and background furnished by Frank Rockett of Airpax Products Co.

that there is no neutral position of the movable arm when de-energized; the arm and its contact will stop at random on either of the fixed contacts when drive is removed.

Cho ers are most frequently packaged in hermetically sealed, cylindrical housings of the order of 3 inches high and 1 inch in diameter. Connections are brought out to socket pins that plug into 7-pin miniature or octal tube sockets permitting simple and speedy installation or removal.

CHOPPER DEFINITIONS

Off Time. Off time is the time in degrees during which neither contact is closed; it occurs twice in each cycle.

Dwell Time. This is sometimes called "on time." It is the number of degrees each contact is closed, expressed in relation to the driving sine wave. There are two dwell time intervals in each cycle of operation as illustrated in Fig. 6-3.

Balance. Balance is the difference between dwell-times on the two fixed contacts, expressed in degrees.

Common Time. Common time (see Fig. 6-4) occurs in a make-before-break chopper and is the period during which all contacts close together. Measurement of common time provides a more accurate and more easily measured control of balance.

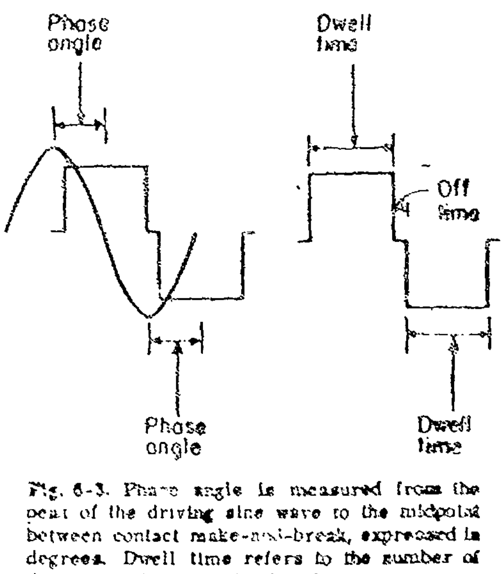


Fig. 6-3. Phase angle is measured from the peak of the driving sine wave to the midpoint between contact make-and-break, expressed in degrees. Dwell time refers to the number of degrees each contact is closed.

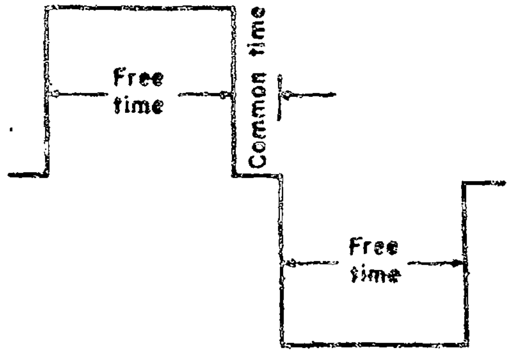


Fig. 6-4. Common time defines the interval during which all contacts are at the same potential. It occurs only in make-before-break choppers.

Make or Closure Angle. The angle of contact closure (see Fig. 6-6) is measured from the point at which the driving sine wave crosses the zero amplitude axis to the point of first contact closure. The breaking angle is referred to the same point in time.

Phase Angle. The phase angle is the angle existing between the peak of the driving sine voltage and the midpoint between contact make and break, expressed in degrees of the driving wave, as shown in Fig. 6-3. Thus, phase angle is measured from the 90-degree (or 270-degree) point of the driving sine wave to the midpoint of the on time or period of closure.

Relative Phase. Relative phase is the phase polarity of the chopper. It is most easily defined in terms of the required d-c polarity on the coil to close a specific contact. Reversal of coil or contact leads introduces a 180-degree change in signal position.

Frequency Range. Frequency range is the range of drive-coil frequencies over which satisfactory operation can be obtained.

Noise. Noise is the residual noise or signal appearing across resistors connected to the contacts, as shown in Fig. 6-6, with excitation applied to the coil and no direct current applied to the contacts.

Chatter. Chatter is the physical bounce or rebound of the contacts occurring after the initial contact closure. Chatter is an undesirable form of off time and is expressed in degrees. If more than one bounce occurs, the total chatter from the beginning of the first bounce to the end of the last bounce is meas-

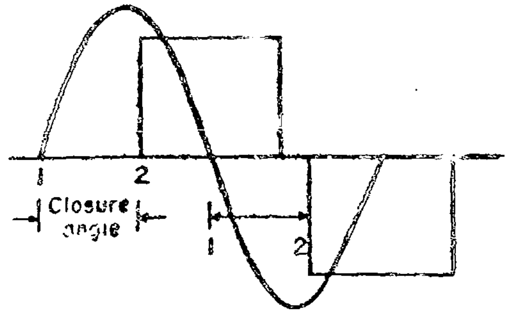


Fig. 6-5. Closure angle is measured between the two reference points of (1) the driving sine wave axis crossover and (2) the actual contact closure.

ured and expressed in degrees. Figure 6-7 shows a typical oscilloscope presentation of chopper chatter.

CHOPPER DESIGN

The design of choppers, like that of any electromechanical device, involves specialized analysis and some compromises for optimum performance. Some of the advantageous features of well designed choppers are:

1. Extremely rugged construction; no delicate or sensitive parts; ability to withstand extremely brutal mechanical treatment without characteristic change.

2. Immunity to vibration and acceleration; this is due to the large dynamic traverse and the high instantaneous stored energies of the system when operated near resonance.

3. Rapid, clean contact make and break.

4. High contact pressures.

5. Large contact wiping action.

6. Insensitivity to thermal expansions and contractions altering the internal spacings. This again is due to the large dynamic traverse that requires no hypercritical spacings or adjustments.

Some of the disadvantages of choppers are:

1. Mechanical wear on the contacts.

2. Dependence of phase angle on frequency, which, however, can be held to practical tolerances for variation usually encountered in drive frequency.

Contacts

The service life of any chopper is invariably limited by contact behavior. The contacts are subject to failure because they may wear, pit, stick, transfer metal from one contact to the other, and develop resistance. In low-

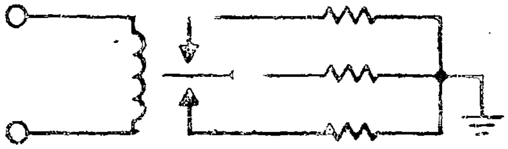


Fig. 6-6. Circuit configuration for measurement of noise values.

level applications, where the interruptions involve small voltages at high impedances, little effect is noted from the electrical phenomena that are most troublesome with vibrator contacts where power must be handled. The wear seems to be mainly mechanical.

Factors affecting the abraded volume of contact metal are: contact shape, choice of metal, hardness and crystal structure, contact pressure, distance of wiping, and atmospheric conditions.

Large dynamic traverse, resulting in large wiping and high contact loads, is beneficial for reliable operation.

Because choppers handle information signals, some contacts are of relatively soft material, often gold, and need not be widely separated when open.

Contact Resistance. Chopper contacts are occasionally prevented from making completely and adequately so that the output waveform appears ragged and distorted. The cause is the presence of nonconductive or semiconductive matter in finely divided powder form on the contact mating surfaces. One contributing factor is the accumulation of oxidation products. The effect on circuit opera-

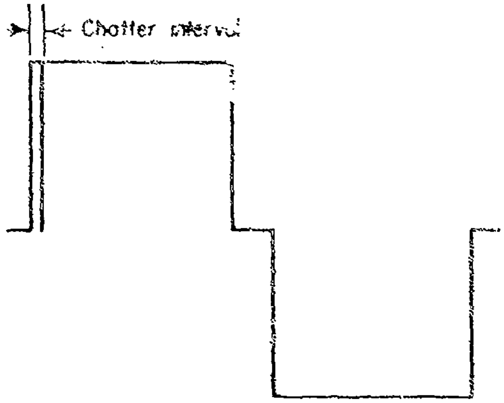


Fig. 6-7. Oscilloscope presentation of contact chatter or "bounce."

tion is that of a resistance in series with the chopper contacts so that the circuit to be closed by the contacts, perhaps the grid of an amplifier, is actually closed through a variable resistance.

The erratic signal resulting from this phenomenon is sometimes classified as noise. In a stricter sense, this erratic behavior does not create a new signal but, rather, a highly distorted version of the existing signal. Choppers exhibit this tendency in varying degrees, and the quality of the chopper may be established on this basis alone. Chopper life is usually terminated with the onset of appreciable contact resistance.

Mounting Considerations

In Fig. 6-8 are the mounting details and dimensions of some of the more frequently used chopper types. Basically, two classifications exist: one type merely plugs into a conventional tube socket; the second is mounted by metallic straps or collars, and secured to the chassis with nut and bolt assemblies.

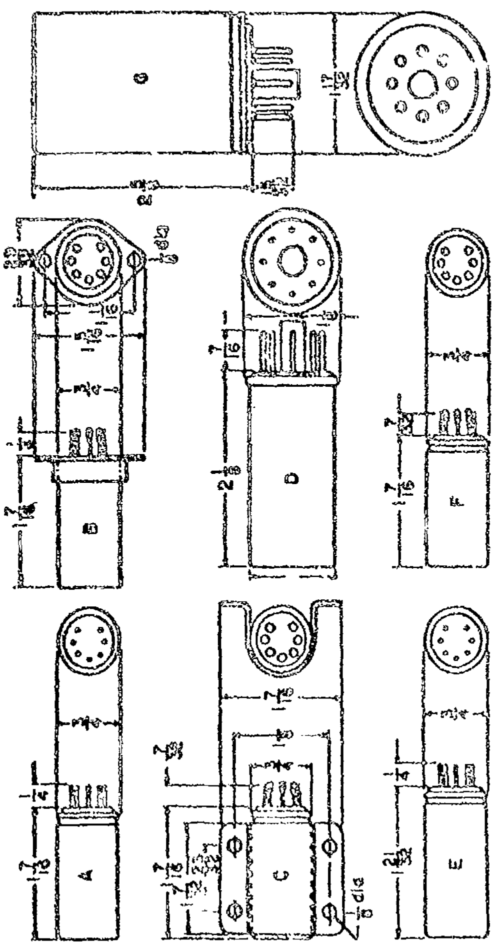


Fig. 6-8. Physical details of typical choppers.

Socket Connections. Plug-in choppers mate directly with the specified tube socket. Other choppers employ solder lugs with openings for the attachment of necessary lead wires. Where isolation between input and output is important, the contact leads are brought out of the chopper case at the bottom while the drive-coil leads exit at the top.

Socket connections are generally printed on the top of the choppers. A variety of connections is illustrated in Fig. 6-9, which covers the two types of bases, 7-pin miniature and octal.

Types of Choppers Available

Manufacturers can supply, as stock items, choppers designed to operate at practically any frequency from 15 to 1800 cps and from 6 to 120 volts. Common frequencies are 60, 400, and 500 cps; typical voltages are 6, 12, 18, 26, and 120. A typical 120-volt, 400-cycle chopper will consume approximately 1 watt of drive power. A typical 6.3-volt, 60-cycle unit requires 20 ma current. Characteristics of typical choppers are given in Table 6-1. In general, choppers weigh from one to several ounces.

ENVIRONMENTAL CONSIDERATIONS

Choppers are influenced by external environmental conditions to an extent that is measurable. These environmental conditions are specifically temperature, frequency, voltage, shock, vibration, humidity, corrosion, atmospheric pressure, and aging. Phase angle and dwell time are the parameters most affected. Balance and noise change only slightly, if at all, and the change usually can be neglected. Since most choppers are hermetically sealed, salt spray and altitude have a greater effect on the socket than on the chopper.

Variation in Driving Frequency

A 400-cycle chopper is usually designed to operate between 380 and 420 cps. Figure 6-10 shows typical phase angle, dwell time, and balance changes over a frequency range of 360 to 440 cps. It will be noted that the phase angle between the driving voltage sine wave and the chopper contacts increases as fre-

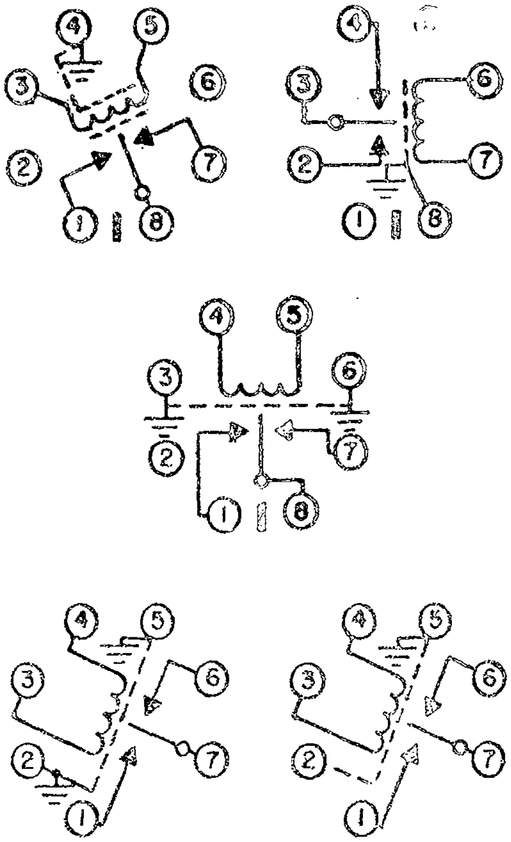


Fig. 6-9. Typical diagrams of internal chopper connections.

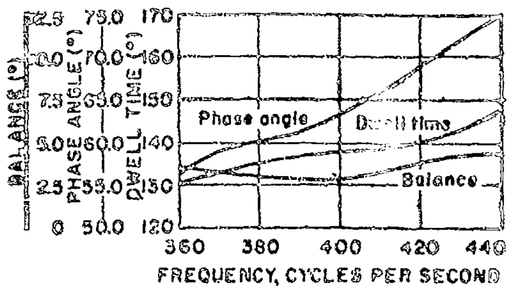


Fig. 6-10. Effects of driving frequency variation on balance, phase angle, and dwell time.

quency rises; similarly, dwell time occupies a greater portion of the contact cycling interval as frequency increases. Balance is at a minimum at the nominal operating frequency and rises slowly as the operating frequency departs from nominal. The use of an external phasing network to permit operation at zero phase angle improves the chopper reaction to variation in driving frequency as shown in Fig. 6-11.

Variation in Temperature

The effects of temperature changes on the phase angle and dwell time of a typical chopper are illustrated in Fig. 6-12. A considerable part of the phase change is electrical and is due to the change in resistance of the copper wire of the coil. The curves of Fig. 6-12 are

Table 6-1—Operating Characteristics of Representative Chopper Types

Drive voltage (volts ±10%)	Frequency (cps)	Dwell (elec. degrees)	Balance (elec. degrees)	Phase (elec. degrees)	Noise (mv*)	Temperature (deg C)	Max rated values (volts, ma)	Diagram (See Fig. 6-9)
6.3	400±40	140±35	15	65±25	3.0P-P	-55 to +200	100, 2	G
6.3	400±20	140±25	15	65±25	3.0P-P	-55 to +200	100, 1	A
6.3	60 ± 6	167±10	10	20± 5	0.1rms	-65 to +100	100, 1	D
6.3	60 ± 6	167±10	10	20± 5	0.1rms	20	100, 1	A
6.3	400±20	147±10	15	65±15	1.5P-P	-65 to +100	100, 2	A
6.3	400±20	147±10	15	65±15	1.5P-P	-65 to +100	100, 2	C
6.3	400±20	147±10	15	65±15	1.5P-P	-65 to +100	100, 2	B
6.3	400±30	147±10	15	65±15	1.5P-P	-65 to +100	100, 2	F
6.3	400±20	140±25	20	90±20	3.6rms	-55 to + 85	100, 2	G
120	applied through external correction circuit to produce zero phase angle							
	400±20	140±25	15	0±30	5.0rms	-55 to + 85	100, 2	G
6.3	60	158±10		50±30	2.0P-P	-75 to + 85	100, 2	G
26	400±20	140±35	15	75±15	4.0rms	-55 to + 85	100, 2	G
6.3	400±20	140±35	15	65±15	3.0P-P	-65 to + 85	100, 2	G
6.3	400±20	144±22	15	60±10	2.0P-P	-55 to + 85	100, 2	G
6.3	100	144 min	15	50±15	3.0P-P	-55 to + 70	100, 1	G

* P P = peak-to-peak
rms = across 1 megohm into circuit having bandwidth from 20 cps to 50 kc

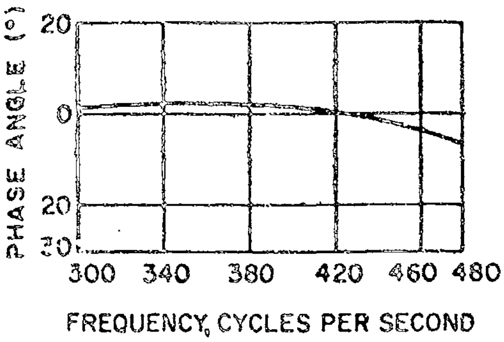


Fig. 6-11. Phase angle variation with frequency with use of external phasing network, 115-volt 400-cps chopper.

taken with 6.3 volts, 400 cps applied to the drive coil. The dotted lines indicate maximum and minimum values of the sample lot selected.

Variation in Drive Voltage

Variations in applied driving voltage will cause changes in phase angle, dwell time, and balance. Typical measurements are shown in Fig. 6-13.

Distribution of Phase Angle Over Production Lots

The distribution of phase angle with production lots introduces a variable to be considered by the equipment design engineer. Figures 6-14 and 6-15 attempt to give some idea of the variations that can be expected from a production lot of 100 choppers selected

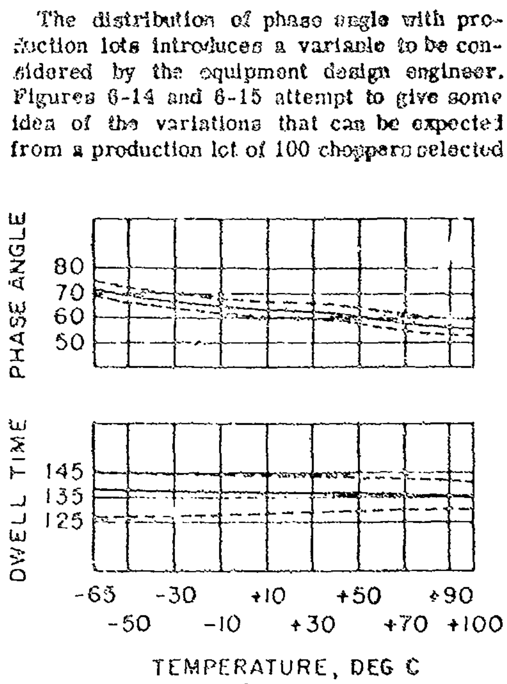


Fig. 6-12. Effect of temperature variations on phase angle and dwell time.

at random. Figure 6-14 illustrates the measured phase angle with 6.3 volts, 400 cycles applied. Figure 6-15 shows the measured phase angle of the same group but using the phasing network shown in Fig. 6-16 to permit operation at zero phase angle, 115 volts, 400 cps.

Variations with Aging

Life tests of typical choppers under normal specified conditions indicate that the change in phase angle up to 3000 hours would be less than ±5 degrees and that the change in dwell time would be slightly greater.

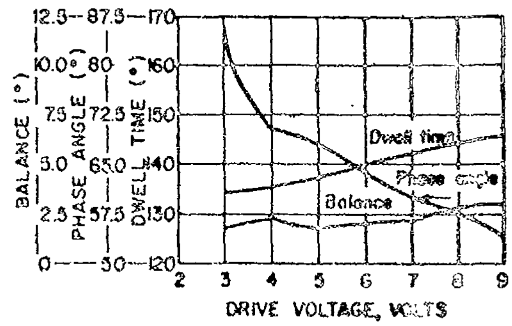


Fig. 6-13. Effect on balance, phase angle, and dwell time of variation in drive voltage level.

Electrical Characteristics

The current commercial market supplies stock choppers constructed to withstand tests of at least 200 volts rms from contacts to the case and from the coil to the case. Typically, insulation resistance is higher than 100 megohms from the contacts to the case and higher than 10 megohms from the coil to the case.

Temperature Ratings

In general, manufacturers rate their choppers to operate within the range of approximately -55 to 85 C, although some are stated to perform satisfactorily down to -65 C and up to 125 C. A particular unit has a phase angle of 75 degrees at -65 C and approximately 64 degrees at 130 C with values very close to 65 degrees over the range of 0 to 85 C.

One manufacturer states "although a temperature gradient along the reed . . . . in excess of 1 deg F would generate a maximum of approximately 10 microvolts stray emf pickup, the existence of such a gradient is minimized by the use of high thermal conductance for the reed assembly."

On special order, choppers are available for unusual temperature conditions of short-time or extended operation.

Vibration and Shock Resistance

Without deterioration of waveform, stock items will withstand extended vibration to 10 g from 10 to 55 cps and are constructed to withstand repeated shocks of 30 g in any direction for 11 milliseconds. More recent miniature units operate under vibrations up to 30 g at 5 to 2500 cps and withstand 100-g impacts along all principal axes.

Atmospheric Environments

Hermetically sealed choppers, often in dry nitrogen, will operate at any altitude up to 50,000 feet. Most of them are treated and painted to withstand salt spray and high humidity unless condensation occurs around the socket pins.

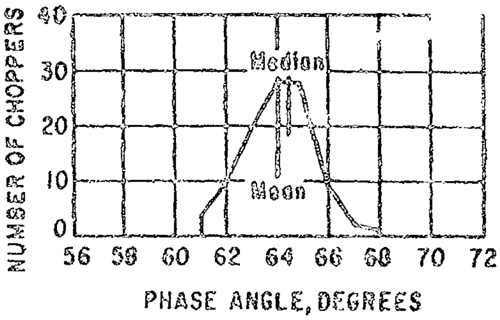


Fig. 6-14. Distribution of phase angle in a typical production lot of a 6.3-volt, 400-cycle chopper.

APPLICATION CONSIDERATIONS

In many applications, a prime source of trouble arises from the use of a single chopper to perform the functions of modulation and demodulation. This seems to occur because the output is brought to the same tube socket as the input. One cure is the use of a make-before-break chopper so that at least one end of the amplifier is grounded at any given instant. If such a chopper jitters, or the contacts wear so that it loses its shorting action, the circuit is abruptly disabled by internal oscillation.

If the chopper fits in a septal socket, grounding the center bayonet of the socket and using shielded leads helps considerably since most of the coupling capacitance resides in the tube socket itself. Rolling off the response of the a-c amplifier just above the carrier frequency by adding shunt capacitance also helps.

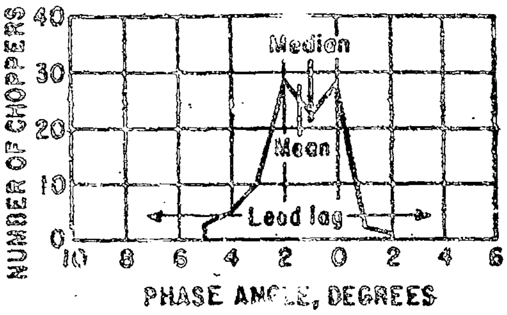


Fig. 6-15. Distribution of phase angle in production lots; 115-volt, 400-cycle chopper types, using external phasing network.

If gains above 30,000 are necessary, the recommendation is to use two separate choppers, one for modulation and one for demodulation. While this may seem extravagant, it is generally feasible on the basis that d-c amplifiers seldom come singly. Many applications require multichannel recording (operational amplifiers usually come in pairs) so that often one chopper can modulate the input to two amplifiers and the other demodulate both outputs, thus preserving the ratio of one chopper per amplifier.

NOISE

Because choppers are very often employed in null circuits, it is most important that they

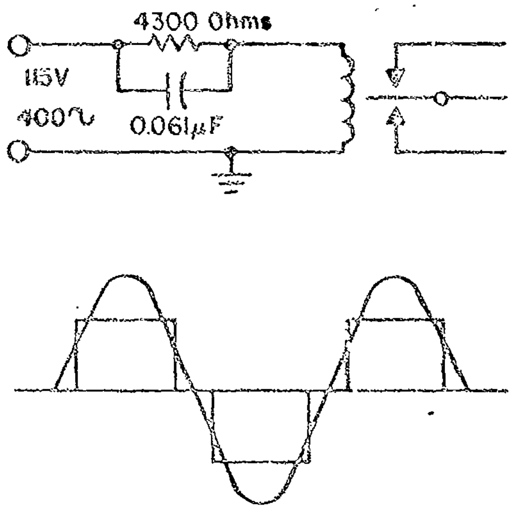


Fig. 6-16. Reactive network for manipulation of phase angle.

produce little noise or pick up little extraneous noise. Commercially procurable units are described by the manufacturers as having noise of the order of a few millivolts across 1/2 to 1 megohm from contact to ground. Some units produce as little as a few microvolts. One unit is described as having a stray electrostatic pickup of 2×10^{-10} volts per ohm of input circuit impedance and an electromagnetic pickup of 2×10^{-6} volts.

A discussion of the noise problem is given below as it forms the basis of an understanding of the principles of chopper action and will enable the user to understand their proper application.

Sources and Types of Noise

An ideal switch would be intrinsically noise-free. Such operation, however, is impossible to attain from a device that possesses physical mass and that initiates and terminates the flow of electric current in a rapid manner by means of contacts. The output as shown in Fig. 6-17 can generally be used to discuss the noise problem. It shows a moving contact alternatively connecting an amplifier grid to a source of voltage and then to ground potential. The unused contact in this diagram may be employed to demodulate the amplifier output or to modulate another amplifier input.

Chopper noise is of two general types, electrostatic and electromagnetic.

Electrostatic Noise. For the present purpose, discussion of electrostatic noise is limited to pickup from the driving coil of the chopper. In Fig. 6-18(A), C_1 and C_2 are stray capacitances from either end of the coil to one of the fixed contacts. This circuit is redrawn

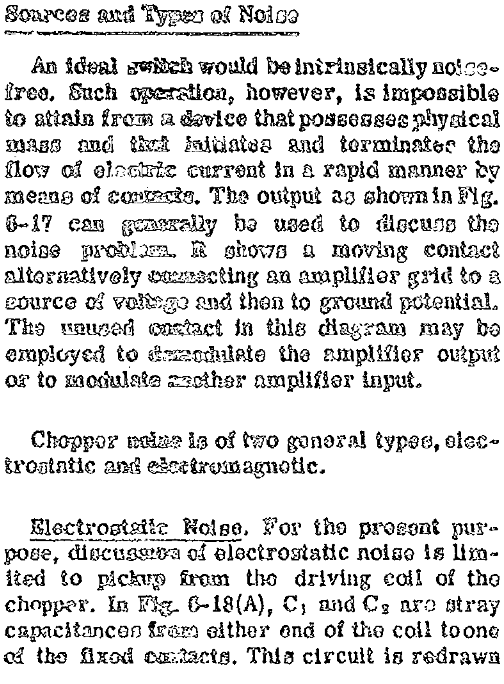


Fig. 6-17. Circuit undergoing evaluation for noise components.

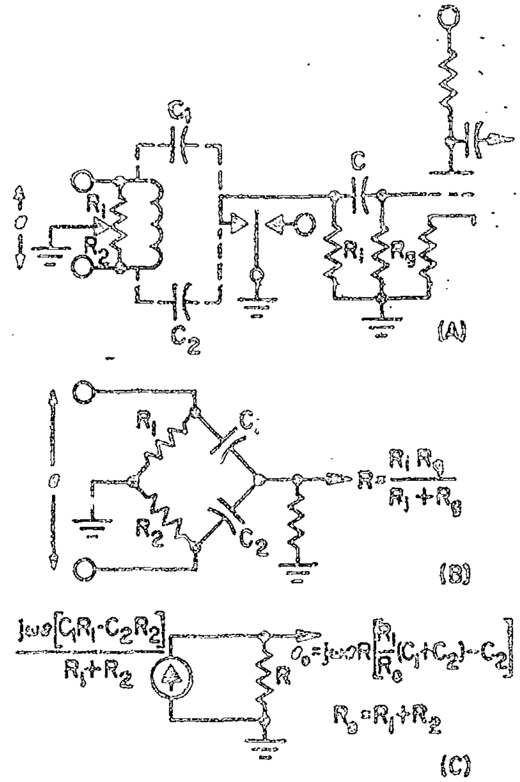


Fig. 6-18. (A) Circuit of Fig. 6-17 redrawn to include stray coil capacitances and coil balance to ground. (B) Redrawn in bridge form with lumped resistances. (C) Simplified equivalent circuit with expression for noise appearing on tube control grid.

in Fig. 6-18(B) in bridge form with R_1 and R_g lumped in parallel and assuming negligible source impedance. In practice, the reactance of C_1 and C_2 is very high compared to R_1 and R_2. When R_1 and R_2 are in the same ratio as C_1 and C_2, the effects of the two capacitances are equal and opposite so that a null exists. The actual noise appearing on the grid of the amplifier, e_o, is given in Fig. 6-18(C). Because $R_1 + R_2 = R_o$, the constant value of the potentiometer across the coil, it is convenient to choose R_1/R_2 as the independent variable and to study the noise as a function of this variable. The grid noise voltage, e_o, is linear with respect to R_1/R_o and is proportional to $j\omega eR$ with bridge balance at $R_1C_1 = R_2C_2$.

The curves plotted in Fig. 6-19 show the adverse behavior of e_o away from null. Curves 1 and 2 are the results of stray pickup between pins 3, 4, and 6 in a ceramic septal tube socket alone without the chopper plugged in. The points for Curve 1 were plotted without

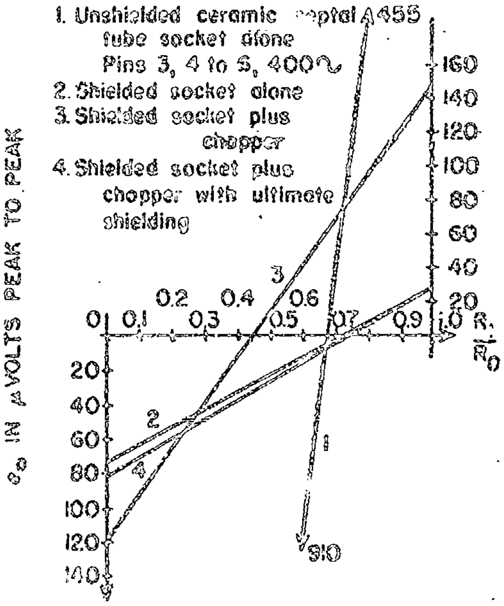


Fig. 6-19. Variation of e_o for several types of shielding.

shielding the chopper or leads. This is the worst possible case. Curve 2 illustrates the condition with shielded leads and the bayonet grounded (the biggest single improvement). Curve 3 shows the effects of added capacitance resulting from plugging a chopper into this shielded socket while Curve 4 represents a laboratory doctored version of the same chopper to show the limits of extravagant internal shielding. For Curve 4, only 6 percent of the pickup is contributed by the chopper.

Excessive solder flux and the hygroscopic behavior of unglazed ceramics can complicate the foregoing analysis by establishing leakage paths across the tube socket, R_3 and R_4 in Fig. 6-20. This not only increases the noise pickup but in general results in a bridge that cannot be nulled. At 400 cycles the reactance of (10^{-9} mf) ($C_1 + C_2$) is very high so that the insulation resistances R_3 and R_4 must be kept high. Teflon tube sockets help.

In applications where noise and amplifier offset are critical, it is helpful to operate the chopper at a frequency differing from that of the main power source, for example, a 400-cycle chopper in a circuit powered by a 60-cycle source or vice versa, so that plate supply hum and filament pickup cannot be converted to effects of either d-c or fundamental chopper frequency.

Observing and evaluating the effects of this electrostatic noise on the output provides significant information about phenomena associated with chopper operation. The noise is sinusoidal and operative during the half cycle the grid is ungrounded. In Fig. 6-21(A) the waveform is shown and described analytically with θ being the angle by which e_o leads the contacts. For a d-c output it is assumed that perfect clamping exists so that the input d-c content appears intact after demodulation.

The phase relationships for a typical chopper with a phase angle of 65 degrees are shown in Fig. 6-21(B). Observation indicates the desirability of a zero phase angle chopper since at $\theta = 90$ degrees, the d-c level vanishes and the fundamental of the noise is in quadrature with the contacts and would, therefore, contribute no torque to a two-phase motor load. Unfortunately, zero phase angle is intrinsically impossible in a mechanical chopper. However, the effect of zero phase is achieved by designing the chopper to have a phase angle of 180 degrees. Reversing the pin connections then adds another 180-degree phase shift with a resultant apparent zero phase shift. Usually, the chopper is designed for as small a phase angle as is consistent with other requirements.

It should be pointed out that for very low noise levels, a simple solution is to employ a chopper whose coil leads are conducted out the top of the case. This destroys, to some extent, the facility of a plug-in arrangement but has the advantage of eliminating pickup almost entirely. Measurements on this type of chopper result in values of e_o barely discernible in the amplifier background noise.

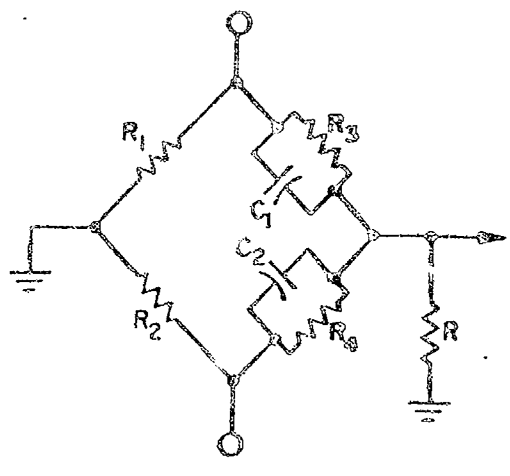
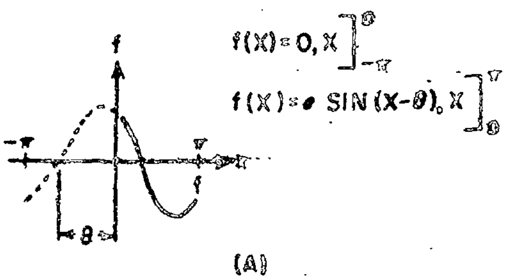


Fig. 6-20. Addition of leakage paths (R_3 and R_4) to circuit of Fig. 6-18(B).



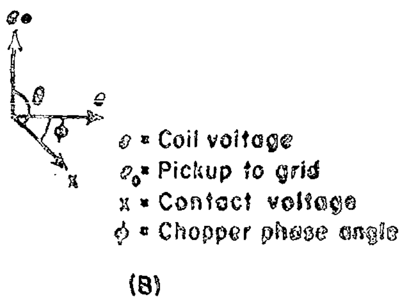


Fig. 6-21. (A) Effects of electrostatic noise on signal output. (B) Phase relationship for typical chopper with phase angle of 65 degrees.

Electromagnetic Noise. During the half cycle the grid (See Fig. 6-22(A)) is grounded, magnetic lines of force from the driving coil intercept the loop so formed and generate a voltage across R_g. Within the chopper case, the magnetic field from the coil intercepts this loop and generates a sinusoidal noise e_m of fundamental frequency as shown in Fig. 6-22 (B). The magnitude of this noise is on the order of 10 to 100 microvolts peak-to-peak depending on the chopper's internal arrangement and magnetic shielding. This noise can not easily be balanced out, but various means can be devised whereby a single turn from a conductor carrying the coil current and the offending loop can be juxtapositioned to cancel the total loop flux. This method is neither consistent nor too practical.

It is wise to connect the chopper ground lead directly to the point where the first amplifier stage cathode bias resistor is grounded, running this chopper lead close to the grid lead to keep the area of the loop small and free from external magnetic fields. Grounding the chassis at distant points is not advisable if low noise is important. This noise is sinusoidal and occurs during the half cycle that the grid is grounded so that Fig. 6-21(A) applies. The magnetic noise e_m is in quadrature with the coil current and so dependent on the mechanical phase lag of the chopper. Fortunately the electrostatic and the electromagnetic noise can be made to cancel each other. This must usually be done by deliberately introducing e_0 and adjusting the coil potentiometer until the noise output is zero. Since e_0 and e_m are both linear in e, variations in coil voltage will not upset the setting; and since they are fixed physical constants, there will be no drift with time.

Investigation of electrostatic and electromagnetic noise phenomena may be aided through the use of the circuit of Fig. 6-23 which permits biasing the reed to one side or another with direct current while a-c excitation is present; the resulting isolation enables one to make individual measurement of the e_m and e_0 noise components. Caution must be observed to avoid overloading the coil with d-c current.

Static Field Noise (Spike Noise). In Fig. 6-24(A), a metallic body A is shown moving away from a positively charged body. The electrostatic field readjusts itself in time so that fewer lines terminate on A but go instead to ground. This requires positive charges to flow from ground to A to neutralize the decreasing electrostatically induced negative charge. The result is a voltage induced across

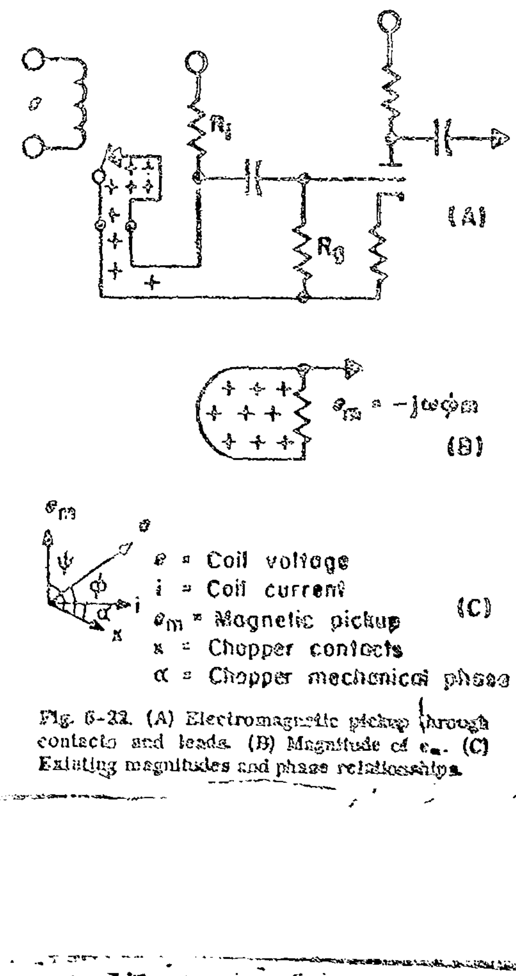


Fig. 6-22. (A) Electromagnetic pickup through contacts and leads. (B) Magnitude of e_m. (C) Existing magnitudes and phase relationships.

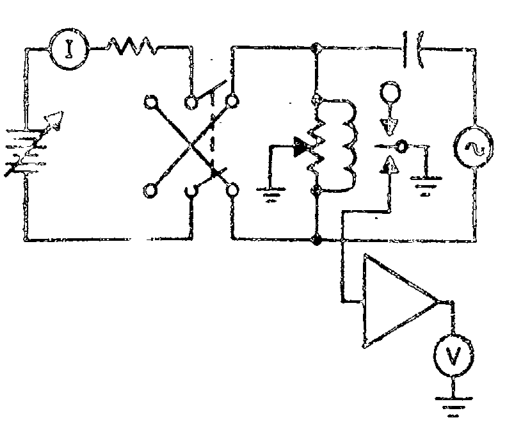


Fig. 6-23. Recommended circuit for measurement of individual noise components.

R due to the mechanical motion of a conductor in an electrostatic field. This fact can explain a large number of noise phenomena where mechanical motion is involved.

For example, mechanical motion will induce frictional static electricity in a large number of dielectric materials. Note in Fig. 6-24 that relative motion of any one body (A, +Q, or ground) with respect to the other two is sufficient. An insulated lead wire, for example, vibrating against a ground plate will generate noise in the wire, the insulation supplying the static electricity and the wire and insulation supplying the needed mechanical motion relative to ground. For this reason, care must be exercised in choosing insulating materials for lead wire jackets, spacers, and shock mounting. Glass, Teflon, and silicon are only a few insulators that show surprising ability to pick up and retain large amounts of frictionally induced static electricity.

Spike noise is occasionally observed in some choppers and is characterized by a pulse of noise occurring just as the contacts break. This pulse has a very sharp rise-time, followed by an exponential decay as shown in Fig. 6-24(B). Investigation has shown this to be merely another form of static field noise. A microscopic quantity of insulating material between the contacts themselves supplies the minute but sufficient static field while the contacts, in the act of separating, supply the necessary relative motion. The spikes always occur in pairs of opposite polarity (one for closing contacts, another for opening) and so contain little d-c and only high harmonic a-c content.

Cable Noise. Shielded cables used on or near a chopper may receive mechanical vibrations and thereby pickup induced noise voltages in the same manner that static field noise is generated. Essentially, this noise is static field noise and is mentioned here for reference; however, this common source of trouble in high-impedance circuits has been eliminated through work done by the National Bureau of Standards (see NBS Technical Report 1645). Noise-free cable is now commercially available from a number of wire manufacturers.

Inverse Leakage. Another noise problem occurs as follows. Refer once more to Fig. 6-17 and assume that capacitor C has a leakage resistance R_c across it, which is periodically shunted across R_g by the chopper contact action. If the tube is drawing grid current, the grid will appear as a constant current source. Let this current be arbitrarily assumed to be 1 microampere, R_g to be 1 megohm and R_c to be 100 megohms. The voltage across R_g varies between 1.0000 and 0.9990 volts as it is successively shunted by R_c. This is equivalent to 1 millivolt of noise

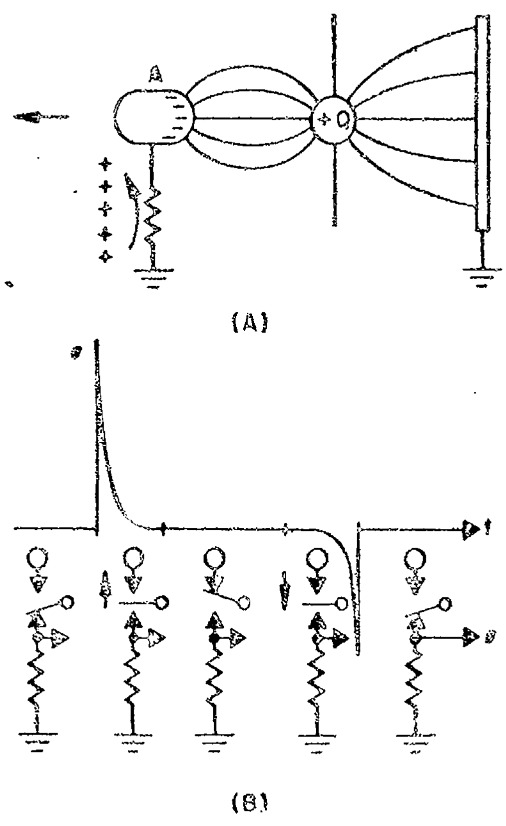


Fig. 6-24. (A) Generation of static field noise. (B) Spike noise generated by contact break action.

at the input. There are two apparent solutions to this problem: (1) Operate the tube with cathode biasing at the grid current crossover point (-85 volts dc for 12AX7) to limit the current and (2) use a high-Q capacitor such as a mica dielectric capacitor that will be relatively free of body leakage paths.

Microphonics. Since the reed in a chopper is of finite mass, all choppers initiate mechanical vibrations to some degree during operation. These vibrations may be propagated through the structure of the chassis or, by means of support members, to low-level, high-gain amplifier tubes. Complete correction may require complex mechanical design analysis beyond the scope of the equipment design engineer. Acceptable measures of success may be had by employing ruggedized tubes, preferably triodes. If it is possible, the input stage should not be placed directly adjacent to the chopper location. An effort should be made to avoid the use of very light gauge chassis metal that can develop and sustain sympathetic mechanical standing waves. The chassis itself, especially if fairly small in mass such as a strip chassis, should be firmly mounted to the more massive sections of the apparatus. Rubber grommets, used specifically as vibration insulators, should be used with caution as they often make the situation worse. Fortunately, microphonics seldom are a major problem and, with a few precautions, are rarely serious enough to cause noticeable effect.

Oscillations Due To Chopper Coupling

The circuit of Fig. 8-25 shows a chopper-amplifier combination in which a break-before-make chopper demodulates its own output. During the switching time of the chopper, the amplifier is floating and the stray capacitance C_3 may cause oscillations. If the feedback is regenerative, high-frequency oscillations result. A good deal of capacitor C_3 can be removed in effect by careful shielding at the tube socket. At voltage gains above 30,000, little more can be done circuit-wise. If the feedback is degenerative, low-end phase shift may cause low-frequency oscillation which, in turn, causes the output to pulsate.

CHOPPER TESTING

From the foregoing discussion of noise, feedback, and microphonics, it is clear that the design engineer should make certain that the unit he selects will perform in the circuit and for the application intended. In any unusual situation the advice of the manufacturer should

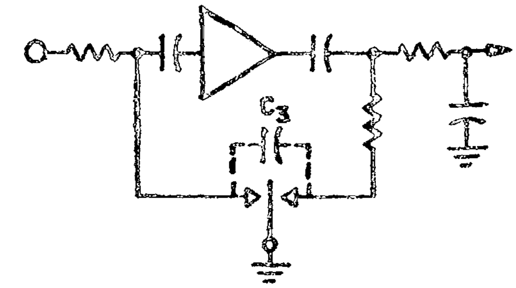


Fig. 8-25. Chopper arrangement for modulation-demodulation.

be sought from the standpoint of saving time and effort as well as from the standpoint of getting the benefit of the manufacturer's experience.

SPECIFICATIONS

The only current military specification is MIL-C-4950(USAF) of 24 June 1955; but as this was being rewritten as of mid-1957, the requirements imposed by it are not included here.

CHOPPER APPLICATIONS

Two broad classifications into which most chopper applications fall are (1) reconciling d-c information with a-c information and (2) amplifying d-c signals. Servo modulators are an example of the first class of application. Direct currents from potentiometers are used in followup loops because of the simplicity of d-c lead and lag networks. The d-c signal is then chopped to provide a signal at the power supply frequency to furnish power to a split-phase motor.

Thermocouple amplifiers are an example of the second class of application. The direct current from a thermocouple is chopped. This chopped signal is then amplified in a conventional transformer, or capacitor, coupled amplifier. The amplifier output is rectified to produce a d-c signal that is an amplified replica of the thermocouple current.

Where low-level d-c signals must be amplified, carefully adjusted tube amplifiers will have a sensitivity of about 10 microvolts. Well balanced magnetic amplifiers can provide long-term stability under varying environmental conditions down to about 5 microvolts, but low-noise instrument-type choppers will provide a sensitivity down to 1 microvolt.

In this application the low-level d-c signal is chopped and passed to an amplifier where the amplitude is brought to the desired level. The amplifier output is fed to synchronously operated contacts on the chopper, which returns the signal to its original form. By accurate preservation of waveform in the amplifier, Offner reports that signal components beyond 70 percent of the chopper frequency can be faithfully reproduced. (1)

Full-Wave Modulator

The circuit of Fig. 6-26 is frequently used to obtain full-wave modulation of a d-c signal. When it is desired to obtain an amplified voltage from a low-impedance source, such as a thermocouple, this circuit is extremely useful. The addition of a capacitor across the transformer will aid in avoiding inductive surges coincident with contact opening and may be used in many ways to modify the output waveform. It will be noted that this circuit resembles that used in vibrator techniques. If appreciable power is to be handled, vibrator and not chopper techniques should be applied.

Demodulator

Full-wave synchronous demodulation is frequently desired and one form of circuit that performs this function is shown in Fig. 6-27. The phase shift device establishes the desired phase relationship between the signal voltage and the chopper contacts. This circuit discriminates against out-of-phase signal components.

Transfer Device

Figure 6-28 is a simple chopper application used to sample the value of an existing d-c

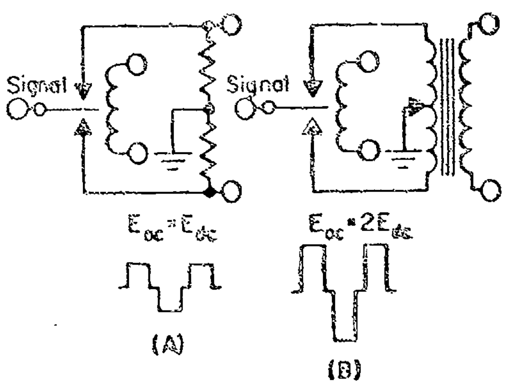


Fig. 6-26. Chopper for use in a full-wave modulation circuit.

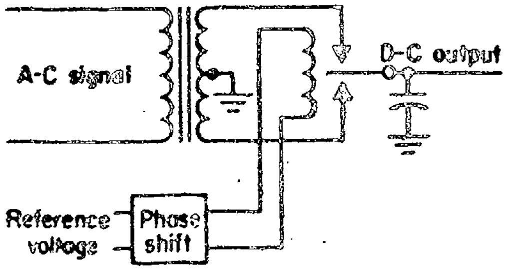


Fig. 6-27. Chopper used in full-wave synchronous demodulation.

level, transferring the information to another amplifier.

Sampling or Time-Sharing Device

Figure 6-29 is a time-sharing device that permits two sets of information signals to be introduced to a common amplifier. Synchronous operation of two choppers is practical, even when the variables of temperature and frequency are introduced.

Modulation and Demodulation

The combination of modulation and demodulation in one chopper is accomplished in Fig. 6-30. The upper frequency limit is about half the chopper driving frequency. There is a loss of signal level from half-wave demodulation. During the off-time of the chopper there is a possibility of oscillation, which is heightened when the amplifier gain is high and the input-output polarities are in phase. Such oscillation is due to capacitive feedback between input and output and can be easily avoided by making this feedback degenerative or by the use of two choppers. Such an application is shown in Fig. 6-31. In a chopper amplifier, the upper limit of frequency response is some fraction

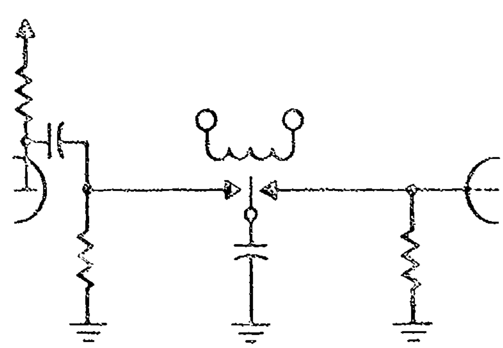


Fig. 6-28. Stage-to-stage transfer of signal by chopper.

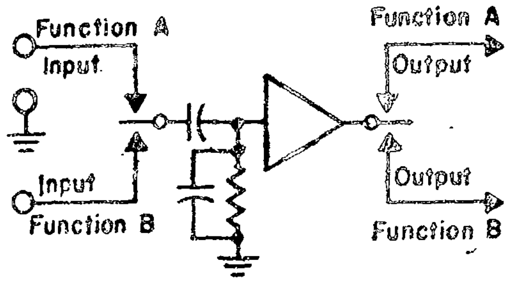


Fig. 6-29. Common amplifier samples two inputs and supplies two outputs through use of chopper.

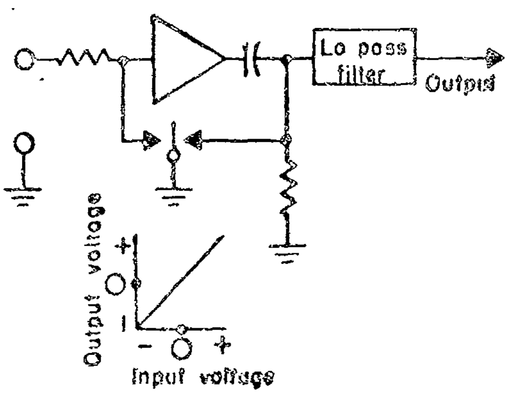


Fig. 6-30. Combining modulation and demodulation in one chopper.

of the chopper frequency. Hence, one simple way of preventing oscillation is to limit the response of the a-c amplifier.

Multiple Use of Choppers

The use of two choppers, as in Fig. 6-31, has particular utility when more than one amplifier is used. This is a frequent occurrence with d-c amplifiers used for computing, in which eight or ten channels may be used, requiring an individual amplifier for each channel. Another method of using two choppers is illustrated in Fig. 6-32. The two choppers are 180 degrees out of phase to provide rectification of the output during the off-time of the input circuit chopper.

Stabilized D-C Amplifiers

To obtain high-speed servo action, a d-c amplifier passing a signal band that extends from some high frequency down to and including direct current is required. This is accomplished by using a chopper amplifier to stabilize the gain and drift of a direct-coupled amplifier, as shown in Fig. 6-33. The chopper periodically grounds the input of the amplifier to provide a zero reference level. The other contact of the chopper reinserts the zero level at the output by grounding the output periodically and 180 degrees out of phase with the input. Applications in this general area are found which use make-before-break choppers to avoid oscillation during chopper off-time. These applications place the extreme burden of reliable performance on the chopper and demand perfect contact action.

Signal Comparators

The comparison of two signals and their subsequent equation to zero, illustrated in

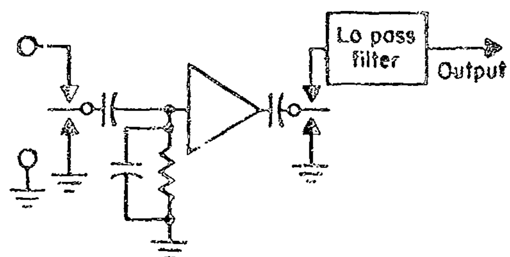


Fig. 6-31. Using two choppers to avoid regenerative feedback paths.

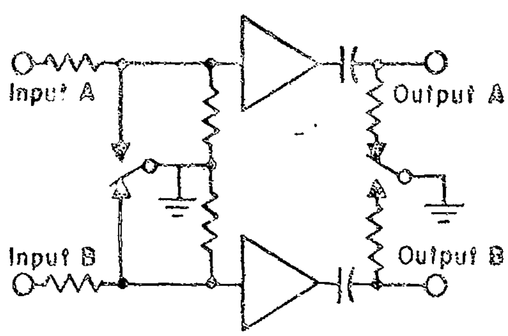


Fig. 6-32. Use of choppers 180 degrees out of phase.

Fig. 6-34, is an application in which choppers find frequent usage. The command control, either a voltage or, as in the illustration, a driven potentiometer position, is compared against another voltage that is the function of a servo-motor position. Any existing error is chopped into a series of pulses and fed to the amplifier to operate the motor in the desired direction. Motor operation is frequently obtained by having the pulses to one of two thyratron tubes. Another approach uses the

chopped and amplified error signal to control saturable reactors that feed the motor.

Bridge Detector Element

As a detector for d-c bridges, the chopper has a number of distinct advantages. It is particularly suited for precision balancing at high impedances. In Fig. 6-35, the chopper is shown sampling both sides of a bridge. The long time-constant of the input capacitance and insulation resistance of the tube prevents the input amplifier from recognizing the chopper off-time. Direct connection to the input grid without excessive loading is possible if the input tube is of electrometer type, having extremely low grid current. The capacitor shown from grid to ground is usually unnecessary

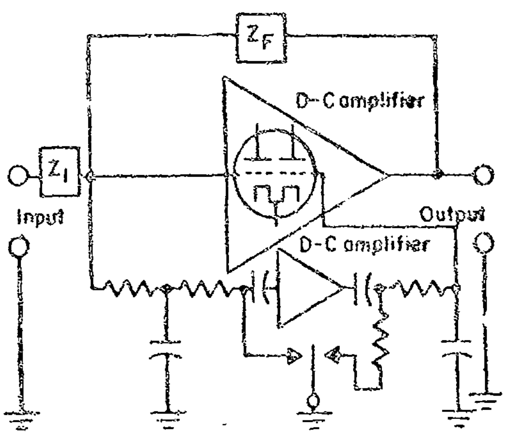


Fig. 6-33. Chopper amplifier used to stabilize gain and drift of direct-coupled amplifier.

since the input capacitance contributed by shielding the grid connection is frequently adequate. In the off-balance condition, the chopper delivers an a-c wave whose phase and voltage are a function of the polarity and voltage of the imbalance. A VX-55 electrometer tube is used. The use of this tube permits direct coupling to the grid because of its low grid current. Bridge-detection sensitivity is enormously improved by the use of the chopper.

R-F Imbalance Detector

Somewhat similar to the bridge detector circuit is the r-f imbalance detector, shown in Fig. 6-36, where a chopper switches a capacitor from one side of an r-f bridge to another to detect the direction of imbalance when it exists.

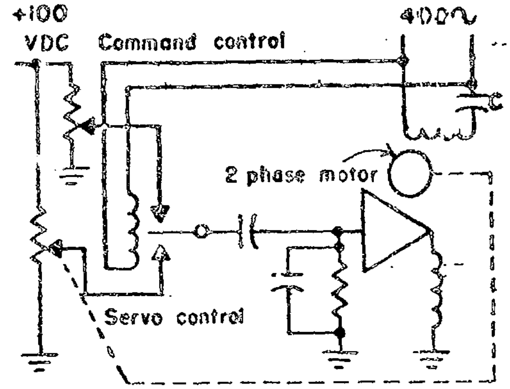


Fig. 6-34. Chopper used for signal comparison in servo system.

Digital-Reading Voltohmmeter

The use of choppers in digital-reading voltohmmeters is a comparatively recent development. Figure 6-37 is a simplified diagram of circuitry that enables an unskilled operator to obtain a direct reading in a-c volts, d-c volts, or ohms, without switching meter scales or interpolating scale divisions. By suitable switching and rectifying, the input signal is presented to one contact of the chopper. Comparison is made to the output of a potentiometer connected to a standard cell. The amplified difference signal drives a servo motor to correct the difference to zero, operating a mechanical counter to provide the digital reading. The output tubes drive the motor directly.

Adjustment of Phase Angle

Certain chopper applications depend on the chopper phase angle being either 0 or 90 degrees. Commercial choppers are available

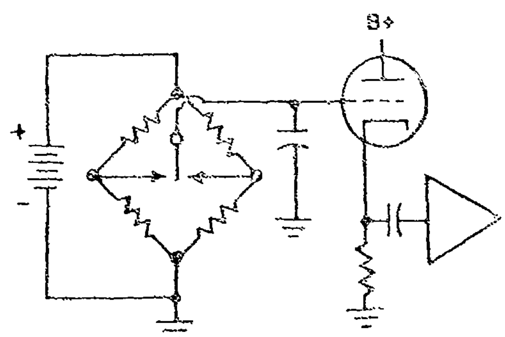


Fig. 6-35. Chopper used as detector for d-c bridges.

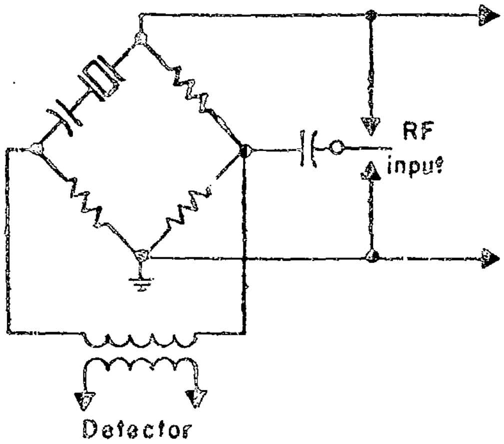


Fig. 6-36. Chopper used in bridge-type r-f imbalance detector.

D-C Drive

Applications may be met where alternating current is not available to drive the chopper. The addition of a buzzer mechanism to drive the contacts is likely to introduce considerable noise at audio and radio frequencies. In addition maximum reliability and stability may be compromised by the need for developing such driving energy. A miniature audiogenerator is available to permit using a d-c power source. The circuit, shown in Fig. 6-38, consists of a highly stable phase-shift oscillator using a dual triode, and requiring only 6 or 12 volts d-c filament power and approximately 250 volts dc. It provides a 400-cycle, 6.3-volt sinusoidal output balanced to ground for minimum noise. The entire assembly is based in a conventional octal tube socket.

that provide a phase angle of 90 degrees without additional changes. Any phase angle other than 90 degrees may be had by using an external phase-shift network in series with the drive coil. Capacitive reactance is introduced to compensate for the inductive component of the driving coil to provide any desired phase relationship between the driving voltage and the chopper contacts. This phase-shift network is illustrated in Fig. 6-16 as used on a 6.3-volt, 400-cycle chopper adjusted for zero-angle operation on 115 volts. A little less than two watts is dissipated in the resistor; component values of 5 percent are recommended.

Techniques for adjusting phase angle vary in efficiency and simplicity with frequency. At 60 cycles the required capacitance values become entirely too large to be practical. Adjustment may be incorporated in the design of the transformer primary or by introducing capacitance into the transformer primary.

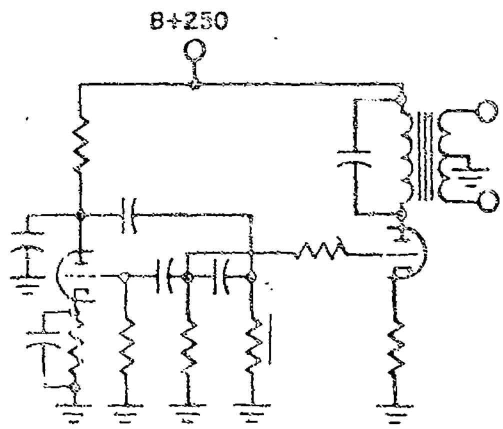


Fig. 6-38. Sinusoidal generator permits chopper operation from d-c source.

High-Speed Servos

Choppers are being used in the design of high-speed servo systems; specific applications occur in several analog computers currently in manufacture. One such design uses a servo possessing a bandwidth of 55 cps, permitting greater accuracy and speed plus smoother low-speed performance. Specifications give a maximum error of 0.5 percent of input at 3 cps, an acceleration of 60,000 volts/sec^2; and at slow speeds, a tracking error of 0.1 percent.

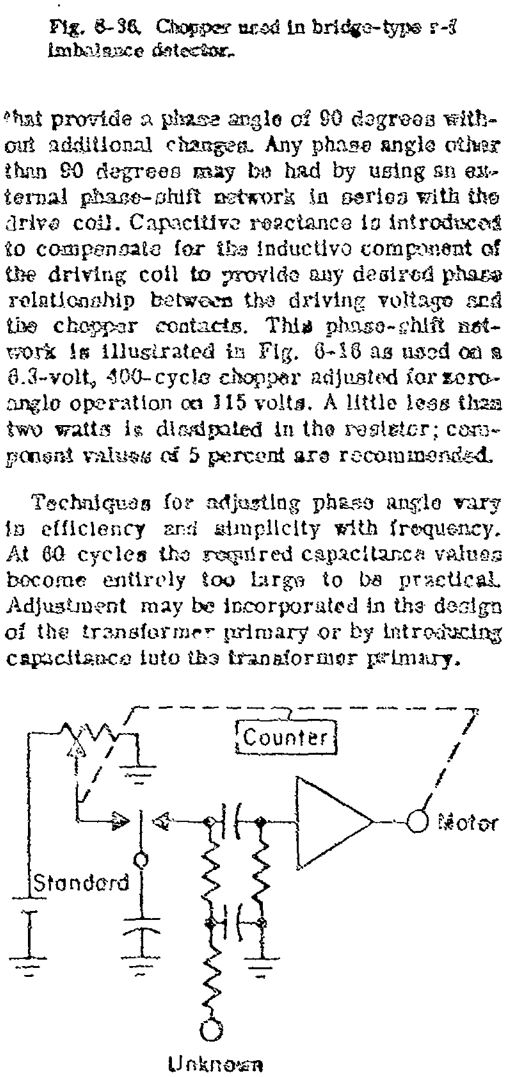


Fig. 6-37. Use of chopper in digital-reading voltohmmeter.

Chopper Amplifier

With the advent of computing amplifiers, the need for stability becomes greater than vacuum tube d-c amplifiers can supply. There

is another system of amplifying direct current called the chopper amplifier in which the direct current is modulated, amplified by RC-coupled vacuum tubes, demodulated, and filtered. Such a system is shown in Fig. 6-39 where one chopper accomplishes both modulation and demodulation. This has the advantage of being free of zero drift but has a limited frequency range. While methods of modulation and demodulation other than choppers, such as magnetic modulators or diode modulators, can be used, these systems invariably utilize two bucking voltages that are unbalanced by the direct current so that matched components must be used. This inevitably leads to drift and offset. The chopper is superior in this respect. The frequency range of this type of amplifier is limited, if not by the output filter, then ultimately by the carrier frequency of the modulator.

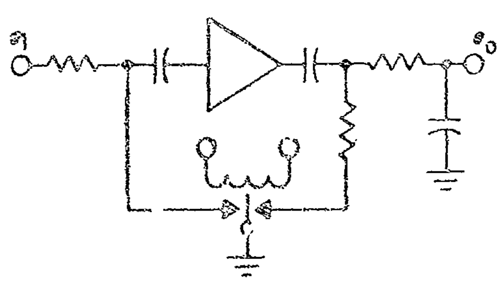


Fig. 6-39. In the chopper amplifier, direct current is modulated, amplified, demodulated, and filtered.

Frequency limitations and undesired offset amplitudes existed as tangible problems still as recent as 1950. (3) The simplest m... of combining two such amplifiers is shown in Fig. 6-40. G is an amplifier, such as that shown in Fig. 6-39, that passes direct current and some low frequencies. A is an amplifier that passes all frequencies not passed by G. By adjusting C_1R_1 and C_2R_2, the frequency responses of each can be matched for a flat response from direct current to the upper limit of A. A difficulty exists in the mixer M, which must pass both direct and alternating current and present a low output impedance. Practical design requires that M must be a direct-coupled vacuum tube and might be most efficiently included in amplifier A. Arranging the circuit in this manner provides the configuration of Fig. 6-41 (A), which resembles the Goldberg circuit. Some reduction of efficiency is implicit in such an arrangement since all the stages of A between the point of application of e_k and the output will contribute their individual drift and offset components to the output. However,

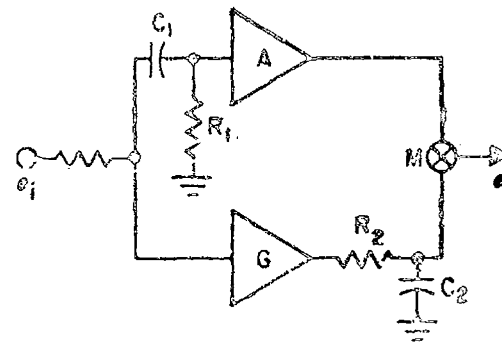


Fig. 6-40. D-C and chopper amplifiers combined to utilize best features of both.

these drifts will be very small compared to the enormous amount of stable d-c amplification coming from G. Hence, e_k may be applied to the input of A and C_1 and R_1 eliminated. Of the two d-c inputs to amplifier A, ϵ and e_k, the latter will usually be many thousands of times the size of the former so that ϵ at direct current is negligible. Thus, we are led to the Goldberg circuit conventionally shown in Fig. 6-41(B) with the feedback resistor now included for completeness.

Unwanted offset can be made quite small by making G very large. Essentially, this is the

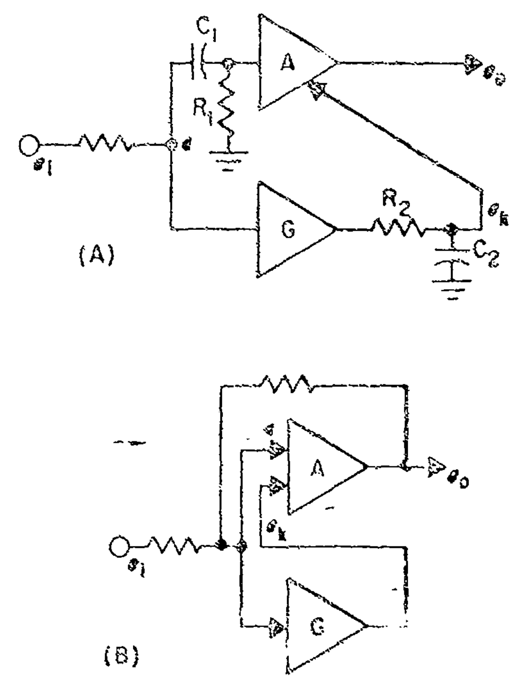


Fig. 6-41. (A) Variation on circuit of Fig. 6-40. (B) Conventional Goldberg circuit.

familiar problem posed in any conventional feedback amplifier; the later the noise is introduced in the amplifier chain, the less effect it has on the output.

CHOPPER CHECK LIST

In selecting a chopper for a specific application, the design engineer should consult the applicable military specification and the manufacturer's catalog literature to determine if a suitable chopper is available from commercial stocks. If a chopper with the necessary qualifications cannot be found in this manner, the manufacturer can supply valuable assistance if he is provided with certain details and requirements concerning the chopper and the function it is to perform. The following check list should be filled out as completely as possible by the design engineer and supplemented by a schematic diagram, when necessary. The manufacturer's engineering staff will then make concrete suggestions aimed at fulfilling the design objective with a minimum of procurement difficulties. The information required is as follows:

1. Available drive voltage_____volts ac, _____volts dc.
2. Contact voltage_____volts.
3. Contact current _____ma.
4. Required contact frequency_____cps.
5. Required dwell time_____degrees.
6. Maximum acceptable noise level_____ millivolts.
7. Isolation between drive and contact circuits. _____Needed_____Not needed.
8. Required phase angle_____degrees.
9. Balance (symmetry of dwell times)_____ degrees.
10. Anticipated environmental temperature (average)_____degrees.
11. Upper temperature limit_____degrees C.
12. Lower temperature limit_____degrees.
13. Relative humidity of operating environment_____percent RH.
14. To sustain shock of_____g of—milliseconds duration.
15. To sustain vibration of_____cps at amplitude of_____ inch, total excursion.
16. To sustain acceleration of _____g for interval of_____seconds.
17. Mounting: _____Plug-in_____Strap.
18. Connections: _____ Socket pins (plug-in) _____lead wires.
19. Size requirements (specify)_____
20. Shape requirements _____
21. Labeling requirements_____
22. Finish requirements_____
23. Case material requirements_____

REFERENCES

1. Offner, F. F., "DC Amplifiers and Direct Recorders," paper read at the Society for Experimental Stress Analysis, Milwaukee Section, 16 January 1957.
2. Goldberg, E. A., "Stabilization of Wide-Band Direct-Current Amplifiers for Zero Gain," RCA Review, June 1950.

BIBLIOGRAPHY

Blecher, F. H., "Transistor Circuits for Analog and Digital Systems," Bell System Technical Journal, March 1953.

Hurley, Richard B., "Transistorized Low-Level Chopper Circuits," Electronic Industries, December 1956.

Kruper, A. P., "Switching Transistors Used as a Substitute for Mechanical Low-Level Choppers," Communication and Electronics, AIEE, March 1955.

McAdam, Will, R. E. Tarpley and A. J. Williams, Jr., "DC Amplifier With Reduced Zero-Offset," Electronics, August 1951.

Robinson, David A., "Operational Amplifier Has Chopper Stabilization," Electronics, September 1956.

Rockett, Frank, "Use Choppers for Control," Automatic Control, November 1956.

Contents

CHAPTER 7 BLOWERS, DRIVE MOTORS, AND FILTERS

Chapter 7

BLOWERS, DRIVE-MOTORS, AND FILTERS

Excessive temperature rise is one of the prime causes of electronic equipment failure. Although the further adoption of semiconductor devices will lessen the problem somewhat, one of the major concerns of electronic engineers will continue to be the dissipation of heat from the equipment as a means of insuring reliability.

The problem has two major aspects: (1) for equipment that is to be used in a fixed location under conditions that are more or less static as far as ambient temperature and altitude are concerned and (2) for equipment that is to be airborne at all altitudes from sea level to 70,000 feet or higher. On long flights the problem resembles that of land-based equipment; but for variable-altitude operation, numerous factors must be considered.

The basic processes for transferring unwanted heat from equipment to the earth's atmosphere are three: radiation, conduction, and convection. This chapter deals with the means for increasing heat transfer by convection; that is, by creating a difference in air pressure by fans or blowers so that (1) the air heated by contact with the equipment is forced out, thereby bringing in outside air or (2) cool outside air is forced into the equipment, thereby forcing out the equipment-heated air. The methods for determining the volume of air flow required, the several types of fans and blowers available, and the use of air filters to insure a supply of clean air are covered.

AIR CIRCUIT PARAMETERS

Constant heat dissipation, preferably at constant equipment surface temperature over the entire operational altitude range of the equipment, is a desirable basic aim of cooling system design. This includes methods for carrying off excess heat by conduction through shields, cooling fins, and heat sinks, plus the supply of cooling air for increasing the heat dissipation by convection. (1)

Calculating the volume of air required proceeds from a knowledge of the heat to be dissipated and the permissible temperature rise within an enclosure.

In considering an air-cooling problem, the design engineer deals with certain parameters associated with these air circuits. These terms and units together with their specific definitions are as follows.

Definitions

Impeller (see Fig. 7-1). Any device used to force air into movement and to control this movement. Normally an impeller is driven by a motor.

Two classes of fan impellers effectively cover all types of fans and blowers commercially available. They are the axial-flow types and centrifugal types. The advantages and disadvantages of each type and a description of the various physical embodiments of these types are given below.

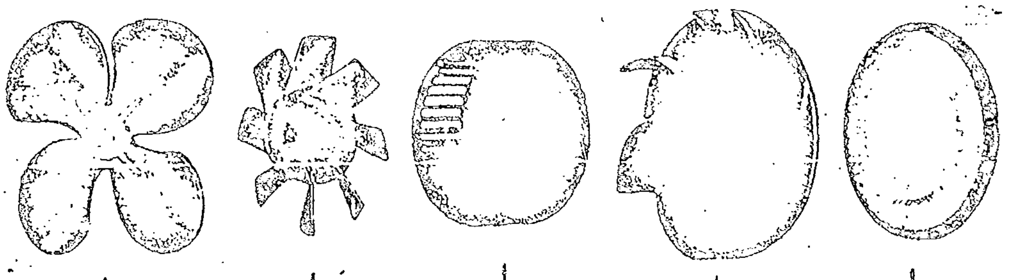


Fig. 7-1. Basic impeller types.

Total Pressure. Total pressure is the rise of pressure from fan inlet to fan outlet as measured by two impact tubes, one in the fan inlet duct and one in the fan outlet duct, corrected for friction to the fan inlet and outlet respectively. Where no inlet duct is used, the total pressure on the inlet side is zero, and no pressure readings on the inlet side shall be taken. Total pressure is an indication of the total energy of air. In blower work, it is measured in inches of water column.

Velocity Pressure. Velocity pressure of a fan is the pressure corresponding to the average velocity determined from the volume of air flow at fan outlet area. It can be determined by a Pitot tube that measures the difference between total and static pressure.

Static Pressure. Static pressure is the total pressure minus the velocity pressure. It is measured in inches of water column by a tube opening normal to air flow. In fan and blower applications, static pressure is never sufficient to compress the air. For example, 1 inch water pressure corresponds to a change of less than 0.25 percent on the specific volume of air. For this reason, the equations used in blower calculations treat air as an incompressible fluid with small error.

Discharge Velocity Pressure. This is a pressure which corresponds to the calculated average velocity at the fan outlet at specified inlet air density and fan speed.

Fan Total Pressure. This is the rise in total pressure (in inches of water column) between the fan inlet and fan outlet at specified inlet air density and fan speed.

Fan Static Pressure. This is the total pressure less the discharge velocity pressure (in inches of water column) at specified inlet air density and fan speed.

Capacity of a Fan. This is the volume rate of flow of air at the fan inlet at any air density and at specified fan speed. The unit of measurement is cubic feet per minute.

Power Input. This is the power supplied to the fan shaft at specified inlet air density and fan speed. The quantity is stated in horsepower.

Air Horsepower. This is the power required to move 1 cubic foot of air per minute against a pressure of 1 inch of water column and is derived in the following manner. Each cubic foot of air per minute moved against a total pressure of 1 inch water column (equivalent to 0.577 ounce per sq in. or 5.19 lb per sq ft) represents the expenditure of energy at the rate of 5.19 ft-lb per minute. The theoretical power required to maintain this flow is

$$\frac{5.19}{33,000} = 0.000157 \text{ hp}$$

Therefore, with perfect efficiency, it will require 0.000157 hp to move 1 cubic foot of air per minute against a total pressure of 1 inch water column (or 6370 cubic feet of air per minute moved against a total pressure of 1 inch will require 1 hp).

Total Efficiency. This is the ratio of the power output of the fan, based on capacity and fan total pressure, to the shaft power input. In formula

$$\text{Total efficiency} = \frac{0.000157 \times \text{cfm} \times \text{static pressure}}{\text{hp}}$$

Fan Outlet Area. This measurement is determined from the inside dimensions of the fan outlet. The outlet area of a fan furnished with a diffuser is the area at the outlet of the diffuser.

Fan Inlet Area. This measurement is determined from the inside dimensions of the fan inlet. For a fan with inlet boxes, the inlet area is that of the box openings.

Pressure Drop. This refers to the difference in pressure existing across a device, such as a filter, placed in the airstream. It is the pressure measured at the upstream end of the device less the pressure measured at the downstream end. The quantity is measured in inches of water column.

Volume of Air Required

For any cooling problem, the volume of air moved should be great enough to limit the temperature rise of the air in the enclosure to a permissible value. The following formula may be used.

$$\text{cfm} = \frac{3170}{T}\text{kw}$$

where T = permissible temperature rise (in degrees Fahrenheit)

cfm = volume of air moved (in cubic feet per minute)

kw = power dissipated inside enclosure (in kilowatts)

This equation permits us to use the volume of air required with known values of permissible temperature rise and power dissipated in heat. In a typical example, a radio transmitter dissipates 2 kw of power within an enclosed cabinet in the form of heat. After a normal warmup interval, the ambient temperature within the cabinet has increased by 60 F. This is 15 degrees more than can be tolerated by a certain component within the cabinet, making the permissible temperature rise within the cabinet 45 F. Using these values, it is apparent that approximately 140 cfm will provide an adequate stream of flushing air. A slightly higher volume of air may be desirable to compensate for nonuniform hot and cold air mixing conditions, although in current practice the safety margin is generally incorporated in the adopted permissible temperature-rise figure. A more complete evaluation of air-rate requirements is presented in Reference 2.

Fan Requirements

The volume of air and the total resistance of the system represent the values which determine the capacity of the fan required for a particular application. The total resistance of the system consists of the resistance of all elements encountered by the air stream, plus the ducting and dust filter when used.

An informative glimpse of the relationship between fan delivery characteristics and cooling capabilities may be had from a theoretical example. A 1/20-hp motor driving a 10-inch propeller-type fan at 1750 rpm will deliver approximately 800 cfm of free air. This quantity of air is capable of handling the dissipation of approximately 3700 watts inside an enclosed cabinet while limiting the ambient temperature rise to 15 F. Twice the air volume may be delivered by increasing the size of the fan and running it at the same speed. The same increase in air delivery may be achieved by doubling the fan speed while maintaining the fan size constant. In the first case, about 3.2 times the horsepower will be needed, but the increased fan size will contribute an increase in noise level. In the second case, the motor will need about eight times the horsepower since horsepower varies as the speed cubed, and again the noise will be higher. The back pressure against which the fan must operate and maintain twice the output will be four times as much at the 3500-rpm speed (compared with the 1750-rpm speed) since static pressure varies as speed squared. It should be noted that when a propeller fan is driven at higher speeds, the static pressure generated by the fan increases with the square of the speed, making it suitable for use in applications requiring such static pressure.

To minimize the back pressure on a fan, the air paths should be kept as direct and unrestricted as practical. Air filters raise the back pressure by 0.15 to 0.20 inch of water column, even when not clogged by dust.

Laws of Blower Performance*

Evaluation of the performance and design of blowers (centrifugal) can be carried out with a reasonable degree of accuracy by applying the so-called fan laws. These laws apply to groups of geometrically similar blowers under conditions of low pressure

*Engineering data for this section was digested from "Fan Engineering," published by the Buffalo Forge Company.

ratio, when compressibility effects can be ignored. Geometrical similarity is taken to imply that variation of the impeller diameter results in change of impeller width in the same proportion. These laws along with the basic relation between pressure rise and head can be stated for incompressible fluids by the following relationships:

Flow volume varies as rotational speed	$Q \propto rpm$
Flow volume varies as impeller diameter^3	$Q \propto d^3$
Head developed by blower varies as impeller diameter^2	$H \propto d^2$
Head developed by blower varies as rotational speed^2	$H \propto rpm^2$
Horsepower varies as impeller diameter^5	$hp \propto d^5$
Horsepower varies as rotational speed^3	$hp \propto rpm^3$
Pressure rise varies as head times density	$\Delta p \propto H\rho$
Horsepower varies as density	$hp \propto \rho$
Horsepower varies as flow volume times pressure rise	$hp \propto Q\Delta p$

In addition to the above stated laws, it is assumed that when the width of the impeller is varied independently of all other operating variables, the flow volume and horsepower will vary in direct proportion to the width and that the pressure rise will remain unaffected. This case of variable impeller width is taken to imply that the impeller is blocked or shielded in varying degrees. The other dimensions of the blower do not vary in a geometrically similar fashion but are constant. Thus, in calculating the performance of a blower that has its impeller diameter and width altered independently, the above width relationship must be applied to the blower whose width is proportional to that of the reference blower in the ratio of the diameters. The assumption of incompressible flow through the blower leads directly to the condition that the pressure rise is proportional to the product of the head and density; thus, even though the head generated by a blower is maintained constant, the pressure-producing ability of the blower can be greatly affected by changes in operating altitude. For example, a blower generating a fixed head has, at 70,000 feet altitude, a pressure production equal roughly to one-seventeenth of its sea-level value.

Example of Use of Fan Laws. As an example of the use of the fan laws and of the basic assumptions that the discharge volume and the horsepower are proportional to the impeller width, assume a blower operating at sea level with a speed of 3000 rpm with an impeller 8 inches in diameter and 4 inches wide. It develops a pressure of 3.5 inches water, delivers 400 cfm, and requires 0.35 hp driving power. Calculate the developed pressure, discharge volume, and required power of a blower with modified impeller width operated at the same percentage of maximum capacity at 70,000 feet altitude, at a speed of 20,000 rpm, and with an impeller 10 inches in diameter and 8 inches wide. In the following, subscript 1 refers to sea-level operation and subscript 2 refers to 70,000 feet altitude operation. The pressure-rise relationship is expressed by a combination of the fan laws

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{rpm_2}{rpm_1}\right)^2 \frac{\rho_2}{\rho_1}$$

This gives for the pressure rise

$$\Delta p_2 = 3.5 \left(\frac{10}{8}\right)^2 \left(\frac{20,000}{3000}\right)^2 (0.0584) = 14.2 \text{ inches water}$$

The discharge-volume relationship is expressed by a combination of the fan laws and by application of the width relationship as

$$\frac{Q_2}{Q_1} = \left(\frac{rpm_2}{rpm_1}\right)\left(\frac{d_2}{d_1}\right)^3 \left[\left(\frac{width_2}{width_1}\right)\left(\frac{d_1}{d_2}\right)\right]$$

$$Q_2 = 400 \left(\frac{20,000}{3000}\right)\left(\frac{10}{8}\right)^3 \left[\frac{8}{4}\left(\frac{10}{8}\right)\right] \cong 13,000 \text{ cfm}$$

The power relationship is expressed by $hp \propto Q\Delta p$ since the efficiency is assumed to be the same because the homologous blower with modified impeller width operates at the same percentage of maximum discharge and should, therefore, have the same efficiency. Thus,

$$\frac{hp_2}{hp_1} = \left(\frac{Q_2}{Q_1}\right)\left(\frac{\Delta P_2}{\Delta p_1}\right)$$

This gives for the power

$$hp_2 = 0.35 \left(\frac{13,000}{400}\right)\left(\frac{14.2}{3.5}\right) = 46.0 \text{ hp}$$

The power can also be determined by a combination of the fan laws ($hp \propto d^5$ and $hp \propto rpm^3$) and application of the width relationship.

BLOWER TYPES

Two general classes of fans or blowers effectively cover all commercially available types. They are the axial-flow types and the centrifugal types. In general it is held, as in the Ohio State Research Foundation report, that the centrifugal blower is best suited to produce constant heat dissipation, preferably at constant surface temperature of the equipment. (2) To meet other requirements, however, or to cope with critical space limitations, the axial fan may be the best selection. Different types of axial and centrifugal blowers are discussed in limited detail below.

Axial-Flow Fans

This type of impeller exists in two broad variations used extensively with cooling equipment. They are the familiar propeller fan and a more refined, somewhat more efficient design using inlet and outlet vanes known as a vaneaxial fan. In both types the air enters and leaves the impeller in a direction parallel to the impeller rotor axis.

In current equipment applications, the axial-flow family of fan impellers functions widely in air-intake capacities and is extremely well suited for flushing large volumes of air over equipment components. This type of fan impeller can be supplied by commercial sources in a variety of sizes and capacity ratings. The materials used in construction include stainless steel, brass, aluminum, and tough lightweight plastics.

Propeller Fans. Propeller fans are widely used for flushing air through chassis compartments and blasting air over heat-generating components. This type of fan, illustrated in Fig. 7-2, is capable of moving relatively large volumes of air for its physical size and horsepower rating. It is not recommended where air is to be moved through restricted areas which develop back pressures appreciably in excess of 0.15 to 0.25 inch of water column. Higher pressures can be provided by special high-speed fans, but these generally produce considerably more air noise.

The air velocity from propeller fans is generally lower than that of a centrifugal blower. The limited pressure-building capacity of a propeller fan does not permit generation of high velocities, because such velocities represent high-velocity pressures. Centrifugal blowers are preferred whenever a high-velocity air blast is required, or whenever air is required to be moved in a relatively narrow duct. Average propeller fans move air at velocities of 500 to 1500 feet per minute (through the propeller area), whereas average centrifugal blowers have outlet velocities of 1500 to 5000 feet per minute.

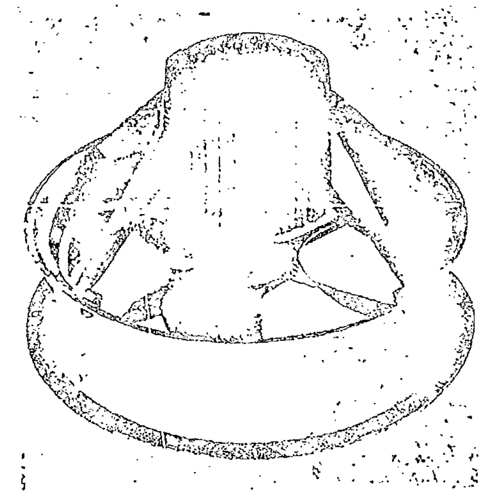


Fig. 7-2. Propeller fan.

A wide variety of propeller fans is available capable of handling air volumes ranging from 10 to 1000 cubic feet per minute at static pressures up to 1.7 inches of water column. Characteristically, propeller fans are small, economical, and rugged and can move large volumes of air at low static pressures.

Vaneaxial Fan. The vaneaxial fan is derived from the fundamental propeller type and belongs in the axial-flow family. Representing a fan design of higher efficiency than the propeller type, it features inlet and outlet vanes (see Fig. 7-3) which utilize the element of whirl imparted to the air by the fan blades to provide an increment of static pressure not attained by the basic propeller-type fan. The vanes also keep the air delivery in an axial direction, establish more uniform flow, and maintain high efficiency with quiet operation. The range of air delivery ratings extends from 20 to 5000 cubic feet per minute at moderate static pressures (up to 3 inches of water column).

Air delivery characteristics of representative axial-flow fans are shown in Table 7-1. The characteristics of eight of these fans have been plotted in the graph of Fig. 7-4 to present an illustration of the typical air volume-static pressure combinations commercially available in axial-flow fans.

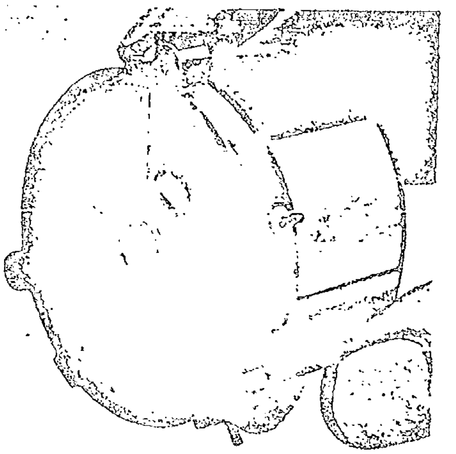


Fig. 7-3. Miniature vaneaxial fan. (Rotron Mfg. Co.)

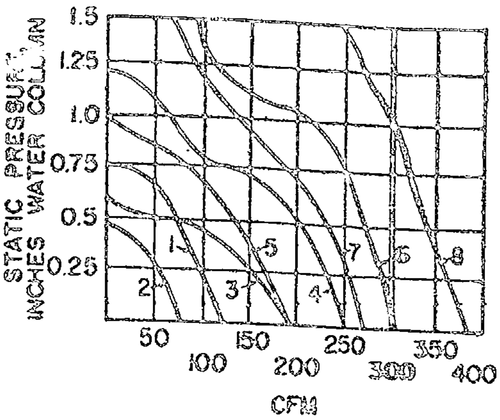


Fig. 7-4. Air delivery characteristics of axial-flow fans. (See Table 7-1 for referenced fan-motor combinations.)

Table 7-1.—Typical Air Deliveries for Axial-Flow Fan-Motor Combinations (See Fig. 7-4 for Associated Curves)

Power source			Air delivery (cfm)		Motor speed (rpm)	Weight (lb)	Curve No. (Fig. 7-4)
Voltage	Frequency	Phases	AMCA*	NEMA†			
115	50–60	1	35	85	3,400	1.1	--
115	400	1	83	240	9,500	1.1	--
115	400	1	113	275	11,000	1.5	1
115	320–1000	1	110	288	10,500	1.1	--
115	320–1000	1	93	250	10,000	1.5	--
208	400	3	98	250	9,500	1.1	--
115	400	3	115	300	11,500	1.5	--
208	400	3	115	290	11,500	1.5	--
208	320–1000	3	93	250	10,000	1.5	--
208	320–1000	3	93	245	9,800	1.5	--
28	dc	--	75	180	7,200	1.3	2
115	50–60	1	82	225	3,250	1.3	--
115	400	1	172	425	6,200	1.6	--
115	400	1	200	515	7,500	1.6	3
115	320–1000	1	135	370	5,400	1.6	--
115	320–1000	1	260	650	9,200	2.6	4
208	50–60	3	95	250	3,500	1.6	--
115	50–60	3	96	240	3,500	1.6	--
115	400	3	200	485	7,000	1.6	5
208	400	3	300	750	11,000	2.6	6
208	320–1000	3	160	410	5,900	1.6	--
208	320–1000	3	270	690	10,000	2.6	7
28	dc	--	165	485	6,200	1.3	--
115	50–60	1	130	285	3,200	1.2	--
115	400	1	215	490	6,000	2.0	--
208	50–60	3	145	285	3,500	1.6	--
115	50–60	3	145	285	3,500	1.6	--
208	400	3	400	820	10,000	2.6	8
28	dc	--	230	435	5,300	1.3	--

* Air-Moving and Conditioning Association. These ratings are obtained essentially under free circulating air conditions, using an anemometer.

† National Electrical Manufacturer's Association. These ratings are obtained by using a Pitot tube mounted in a duct enclosing the discharged air stream.

Centrifugal Blowers

In the centrifugal impeller, the blades are arranged to provide high efficiency by driving the air in a circular orbit within a scroll housing. Considerable centrifugal force is imparted to the air within the scroll, and then the air is expelled through an outlet in a direction tangential to the circle described by the tip of the impeller blades, that is, perpendicular to the axis of impeller rotation and to the axis of air intake. Typical centrifugal impellers are represented by the squirrel-cage blower (see Fig. 7-5). They are used where high pressure and moderate-to-low air-handling capacities are called for and where air-ducting may be desirable. In construction, blower housings, blower wheels, and baseplates are of steel, frequently primed and baked in zinc-chromate. Inlet adaptors may be of steel or aluminum. All steel parts are generally finished in a dull enamel; steel hardware is plated and passivated. Aluminum parts are anodized.

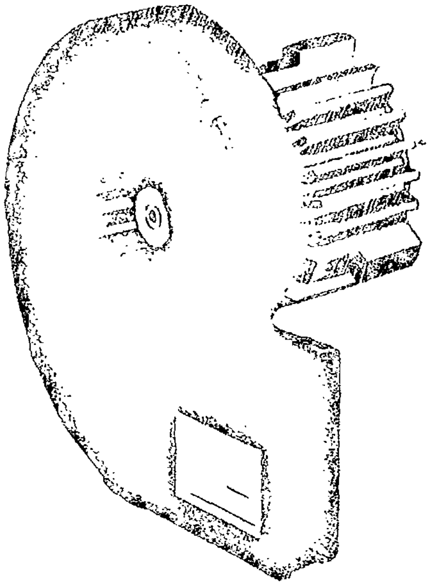


Fig. 7-5. Centrifugal (squirrel-cage) blower (American Electronics Inc.)

Centrifugal Blower Types. Fundamentally there are three different types of centrifugal blowers differentiated from each other by the curvature of the impeller vanes: (1) forward-curved vane, (2) backward-curved vane, and (3) radial vane (see Fig. 7-6). Typical performance curves of a radial-vane type are given in Fig. 7-7 from the Ohio State report. Superimposed on this plot is a system characteristic curve of a typical installation. The back pressure or resistance to flow offered by the ducting and flow path of a system varies as the square of the velocity of air flow. A plot of the back pressure vs. the volume flow results in the system characteristic curve. Where this curve crosses the blower static pressure curve determines the operating point of the blower.

The primary difference between the performance of a forward-curved vane impeller and that of a radial-vane impeller is that the static-pressure curve of the forward-curved vane impeller drops off slightly at small flows to a minimum value, then increases to a peak value, and subsequently drops off like that of the radial-vane impeller. As for the radial-vane impeller, operation of the blower at flows smaller than that for which the maximum static pressure is obtained may become unstable. The horsepower characteristics of both blowers are similar. The pressure characteristics of backward-curved vane impellers are usually such that a slight increase may occur at small flow volumes, followed by a relatively constant pressure over an appreciable range and then a more or less rapid decrease with increasing flow volume. The power characteristics of the same blower differ in that the horsepower does not continue to increase with increasing flow volume and decreasing static pressure but reaches a peak value usually at about two-thirds wide-open discharge. Thus, while a blower with a forward-curve vane impeller, or a blower with a radial-vane impeller, may overload the drive motor when operated wide open (if designed for operation near peak static pressure), a blower with a backward-curved vane impeller has nonoverloading characteristics.

Squirrel-Cage Blower. Squirrel-cage blowers, so called because of the treadmill configuration of their impeller blades, are used

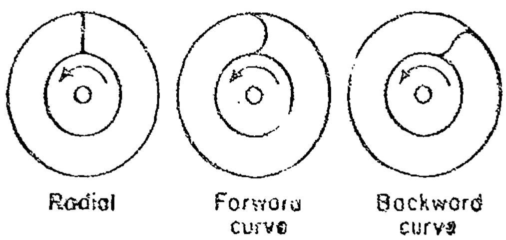


Fig. 7-6. Centrifugal blowers; impeller vane variations.

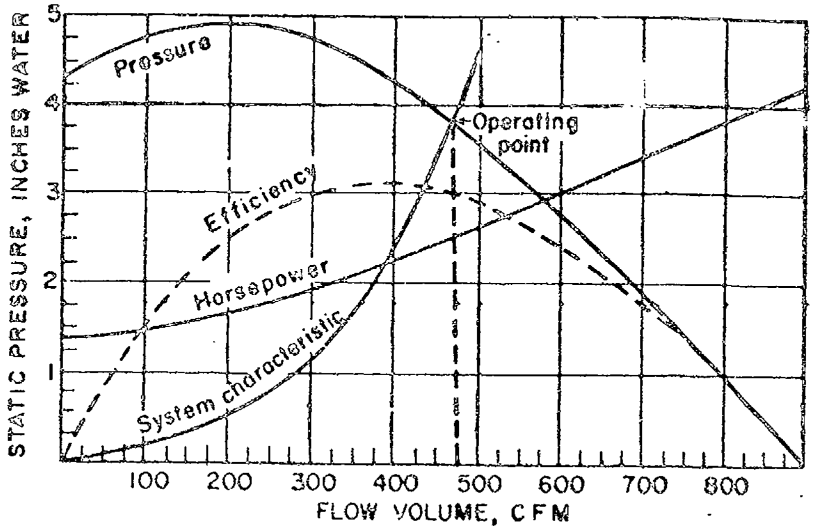


Fig. 7-7. Characteristics of a radial-vane impeller.

where minimum space exists and where ducting may be desirable. Through selection of clockwise or counterclockwise shaft rotation (viewed from motor end) and blast orientation (see Fig. 7-8), this type of blower lends itself to flushing or exhaust applications and can function equally well from an upstream or downstream location. It is capable of moving air volumes ranging from modest values up to approximately 2500 cubic feet per minute at static pressures up to approximately 3.5 inches of water column (see Fig. 7-9 and Table 7-2).

Duplex or double-ended squirrel-cage blowers, as shown in Fig. 7-10, are available and their use can greatly simplify duct-work and allow better operation of equipment, even in tight chambers, than is obtainable with simplex blowers. For centralized cooling systems in instrument or radio transmitter applications, different types of blowers may be combined on a single motor. The additional cooling capacity of such combinations is especially useful when operating in rarified atmospheres and when multiple air streams are desired. Such an arrangement also permits movement of air at two different pressure levels and segregation of air circuits using only one drive motor.

Airtight connections and convenient mounting arrangements can be made by means of the numerous inlet and outlet adaptors available (see Fig. 7-11). A plain inlet may be used to provide a free air entrance to the blower. The use of a cone-type inlet permits the entire blower-motor combination to be mechanically suspended from the flange of the cone. This allows pulling air into the blower from a dust filter or sucking air through a hole in a partition or from an air chamber. When a duct has to be connected to the inlet port for either suction operation or combined suction and pressure, a rim-type inlet is used. The plain outlet port allows a free outlet air blast. The flange outlet represents a method for suspending the entire motor-blower assembly in an airtight manner by

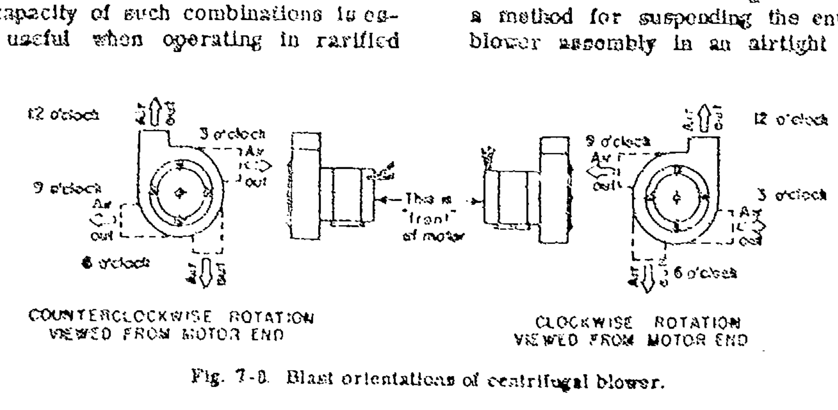


Fig. 7-8. Blast orientations of centrifugal blower.

means of this flange from an air chamber or ca[illegible]et wall.

Radial-Wheel Blower. In applications requiring a considerably higher pressure-to-volume ratio than is obtainable with squirrel-cage-type centrifugal blowers, the single-stage radial-wheel centrifugal blower is recommended. This type of blower assembly, shown in Fig. 7-12, is aimed at the dual objective of high efficiency and minimum space. Its small physical size makes it particularly suitable for being driven at the high shaft speeds obtainable with 400-cycle power supplies used in airborne applications. Even at 50-60 cycles, high pressure-to-volume ratios are possible. Representative volume and pressure figures for this type blower range from 14 to 53 cfm at 3.3 to 9.2 inches static pressure.

Advantages and Disadvantages

Axial and centrifugal blowers each have advantages and disadvantages. In making a selection of a blower type to be employed, these advantages and disadvantages as ap-

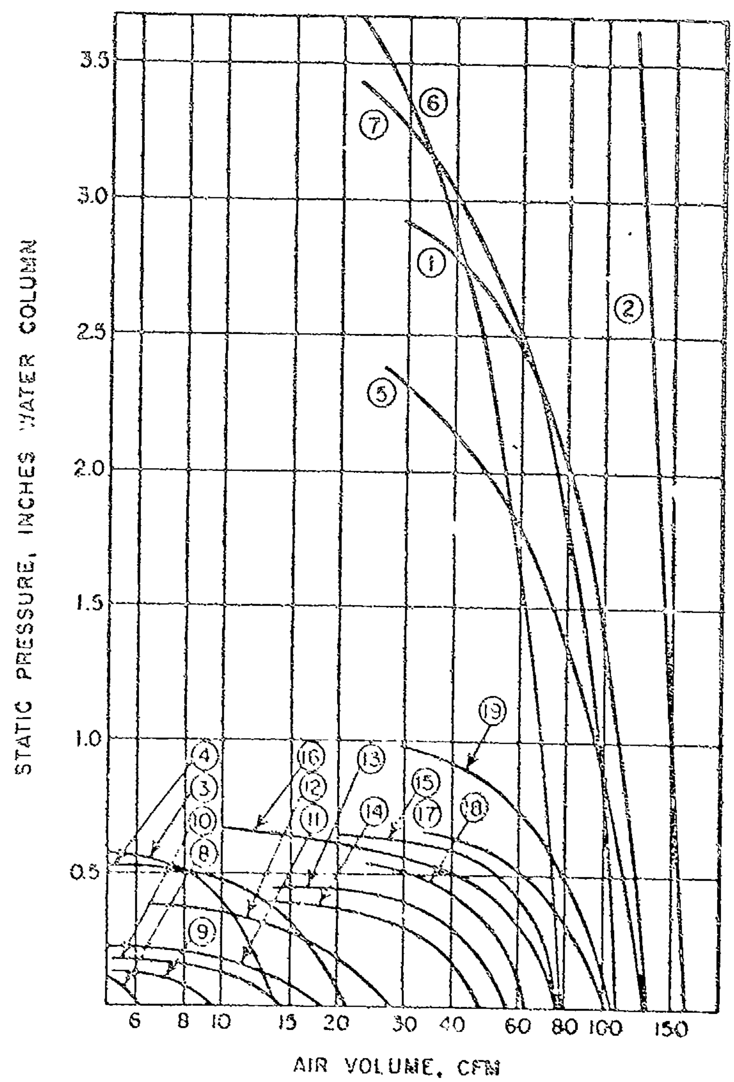


Fig. 7-9. Centrifugal blower characteristics. (See Table 7-2 for referenced fan-motor combinations.)

Table 7-2—Typical Air Deliveries for Centrifugal Blower-Motor Combinations
(See Fig. 7-9 for Associated Curves.)

Power source			Air delivery		Type	Motor speed (rpm, approx)	Weight (lb)	Curve No. (Fig. 7-9)
Voltage	Frequency	Phases	Cfm	Static pressure (in., water)				
28	dc	--	70	1.4	Commutator	3800	3.8	--
28	dc	--	60	1.8	Commutator	3800	3.8	--
28	dc	--	85	1.5	Commutator	3700	3.9	--
28	dc	--	70	1.5	Commutator	3800	3.9	--
28	dc	--	125	3	Commutator	6200	4.4	1
28	dc	--	170	3	Commutator	6200	4.4	--
115	dc	--	120	2.5	Commutator	5400	4.2	--
115	dc	--	80	1.5	Commutator	5500	4.4	--
115	dc	--	135	2.5	Commutator	5200	4.4	--
115	dc	--	90	2.5	Commutator	5500	4.3	--
115	dc	--	96	2.7	Commutator	5000	5.6	--
115	dc	--	150	10	Commutator	7500	9.8	2
115	400	1	13.5	0.43	Cap-run	7000	1.1	3
115	400	1	21	0.6	Cap-run	7000	1.1	4
115	380-980	1	13	0.45	Cap-run	6000	1.1	--
115	380-980	1	18	0.45	Cap-run	6000	1.1	--
115	400	1	100	2	Cap-run	5400	4.8	--
115	400	1	80	1.8	Cap-run	5400	4.9	--
115	400	1	95	1.9	Cap-run	5400	4.9	--
115	400	1	170	1.75	Cap-run	5400	5.8	--
115	400	1	130	1.9	Cap-run	3600	6.8	--
115	400	1	180	2.3	Cap-run	3600	6.8	--
115	400	1	170	3	Cap-run	3600	8.3	--
115	50-60	1	110	2.0	Commutator	5400	4.4	--
115	50-60	1	92	2.1	Commutator	5500	4.7	--
115	50-60	1	135	2.5	Commutator	5200	4.7	5
115	50-60	1	115	2.8	Commutator	5200	4.6	--
115	50-60	1	75	4.0	Commutator	6000	6	6
115	50-60	1	130	3.6	Commutator	8000	4.3	--
115	50-60	1	110	3.5	Commutator	8000	4.8	7
115	50-60	1	150	10	Commutator	7500	9.5	2
115	50-60	1	7	0.1	Cap-run	3400	1.1	8
115	50-60	1	6	0.1	Cap-run	3400	1.1	9
115	50-60	1	8	0.1	Cap-run	3300	1.1	9
115	50-60	1	14	0.22	Cap-run	3300	1.5	10
115	50-60	1	18	0.25	Cap-run	3300	1.5	11
115	50-60	1	28	0.33	Cap-run	3200	1.4	--
115/230	50-60	1	55	0.35	Shaded-pole	3200	5.7	12
115/230	50-60	1	57	0.44	Cap-run	3300	4.8	13
115/230	50-60	1	40	0.35	Cap-run	3300	5	14
115/230	50-60	1	60	0.65	Cap-run	3300	5	15
115/230	50-60	1	75	0.65	Shaded-pole	3200	6	16
115/230	50-60	1	110	0.7	Cap-run	3450	5	17
115/230	50-60	1	100	0.8	Shaded-pole	3300	5.0	17
115	50-60	1	70	0.35	Cap-run	3400	3.8	18
115/230	50-60	1	65	0.5	Shaded-pole	3400	5.1	18
230	50-60	1	103	1.0	Cap-run	3400	5.3	19
115	50-60	1	103	1.0	Cap-run	3400	5.8	19

plied to the installation being designed must be considered.

Advantages, Axial-Type Blowers. Axial blowers have the following advantages:

1. High-peak efficiency. The peak efficiency of axial-flow units of moderate air capacity is 75 to 80 percent. For very small units, these values may not be attainable. However, in comparison, the operating efficiency of a comparable centrifugal blower should be 60 to 65 percent. Therefore, at best efficiency, the axial-flow blower would require 15 to 30 percent less power for operation.

2. High slenderness ratio. By means of multistaging and the use of a high rotative speed, an axial-flow unit of small diameter and appreciable length can be designed that would permit its incorporation in an axial position of a cooling system of small overall diameter.

3. Straight-through air flow. Unidirectional airflow characteristics for such a unit allow its installation in an air duct without complications and without adding the resistance of a collector, elbows, and other devices necessary for installation of other types of blowers.

4. ...ne-angle control. Operating control of an axial-flow blower by means of varying the angles of the rotor and stator vanes and by clutching one or several stages for free-wheeling, when required, is possible. These are methods that may be used individually or in combination to adjust the blower to variable requirements that exist when operation over a wide range of altitude is attempted. However, it must be realized that their application involves considerable mechanical complication that would be difficult to introduce in small units.

Disadvantages, Axial-Type Blowers. Axial blowers have the following disadvantages:

1. Limited operating range. When operating at constant speed, control by throttling or bleeding can only be used over a small range of discharge capacity because the pressure vs. flow characteristic is extremely steep and a small change in blower discharge causes a radical change in pressure generation. At a large percentage of full discharge capacity, the pulsation limit, or instability

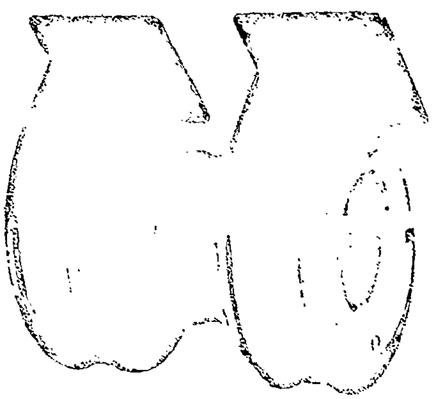


Fig. 7-10. Duplex centrifugal blower. (Sotros Mfg. Co.)

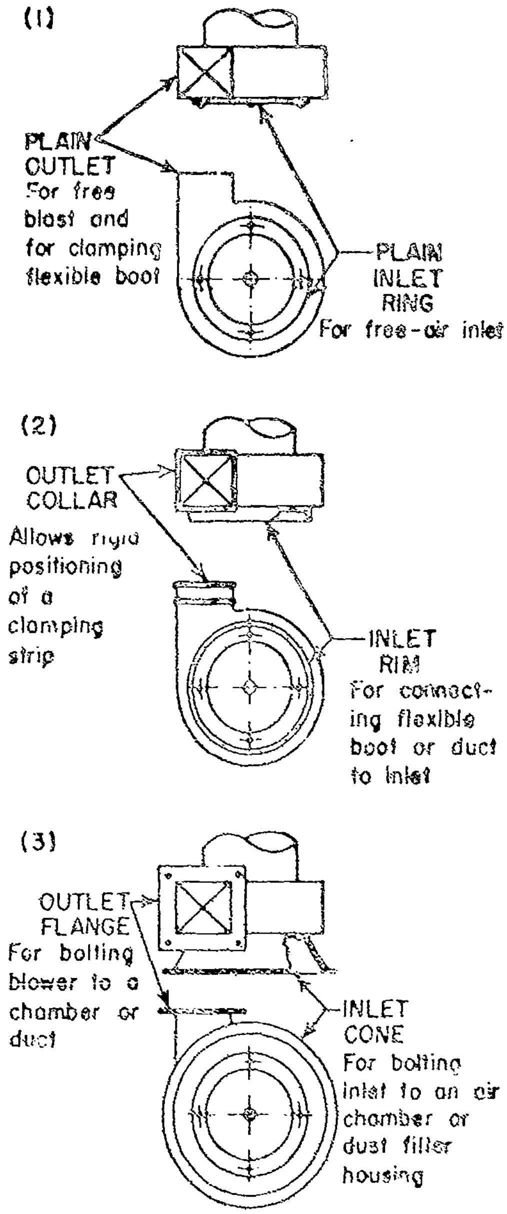


Fig. 7-11. Various styles of inlet and outlet ports for centrifugal blowers.

of operation, is reached, evidenced by a surging or pulsating flow through the blower system.

2. Highly variable efficiency. Although the axial-flow blower has a high peak efficiency, it is not capable of maintaining it with relatively small changes in operating conditions. The efficiency of multistage units is particularly affected by variation of operating

Fig. 7-12. Radial-wheel blower.

speed. Therefore, for applications over a wide range of altitude, the axial-flow blower must be considered as a constant operating-point machine.

3. Length and composite structure. Since the pressure-producing ability of a single stage is small, the need for pressure ratios of two and greater would necessitate many stages. For small units, this may easily lead to excessive length and weight. Also, for such small units requiring several stages, the construction of stator and rotor assemblies would involve considerable complication and higher cost than for equivalent centrifugal units.

Advantages, Centrifugal Blowers. Centrifugal blowers have the following advantages:

1. High pressure ratio. The pressure production per stage is high compared to the axial-flow blower, and it would appear that no more than a single-stage unit would ever be required in the altitude range from sea level to 70,000 feet. This avoids the necessary complications involved in multistaging machines.

2. Light weight. Because of their high head per stage capabilities, such units can be relatively light in weight for a given required pressure production.

3. Flexibility of operation. The operating characteristics are considerably more flexible than those of the axial-flow blower. The permissible variation in capacity at any given speed without encountering an unstable pulsating or surging flow is greater by far than that for the axial-flow unit. Also, the efficiency does not change as abruptly with variation in capacity. For these reasons, control by throttling or bleeding has greater inherent possibilities.

4. Ease of control. For centrifugal blowers, development of control methods seems far more feasible. For example, a centrifugal unit lends itself well to control by variable rotational speed, variable effective impeller width, bleeding, and throttling, all of which can be considered as possible methods of control, individually or combined. Control of pressure production by speed and throttling is effective. Control of volume flow by varying the impeller width, either by movable shrouds or shielding, appears to be possible.

5. Compactness. Centrifugal blowers can be designed to have short axial length, which in some applications may be desirable for greater compactness.

Disadvantages, Centrifugal Blowers. Centrifugal blowers have the following disadvantages:

1. Moderate efficiency. The maximum efficiency of centrifugal blowers is below that of the axial-flow blowers and, in consequence, the power requirements are greater. In general, a peak operating efficiency of 65 percent cannot be exceeded for smaller units such as those under consideration.

2. Large diameter. The overall diameter of the centrifugal blower is greater than that of an equivalent multistaged axial-flow blower.

3. Ducting complexity. The ducting system required for centrifugal blowers is somewhat cumbersome because installations without additional ducts and elbows are generally not possible. Under conditions of great spatial limitations, this may be a serious disadvantage.

Multistage Fans

The placement of two or more fans in a common airstream is termed "staging" and the fans are referred to as "multistaged fans." Usually, the fans are mounted on the same shaft with the necessary partition plates and vanes to direct the air from the outlet of one impeller to the inlet of the next. More often than not, staged fans have identical impellers, but where the pressure rise is great it is better to alter the impeller dimensions so that the maximum efficiency of all fans occurs under the same conditions. The axial-flow fan is particularly well adapted to staging for high-pressure work. Arranged with alternate rows of impeller blades and stationary guide vanes, it gives much the same appearance as some steam turbines. Multistaged axial-flow fans, although not suited for the higher pressures obtainable with radial-wheel fans, are still finding considerable favor.

The net effect of staging fans is that the total pressure is the sum of the individual pressures of each fan rotor while the total capacity is essentially that of one fan.

Blower Location

When a propeller fan is mounted "upstream" as an air-intake device, the cooling air is drawn first over the physical contours of the motor. In this location (see Fig. 7-13) all of the advantages of reduced ambient temperature are provided to the motor, increasing bearing life and improving operating characteristics during motor life. However, most of the power input to the fan motor is added in the form of heat to the airstream which flushes the area to be cooled. This heat rise reduces the allowable temperature rise within the chamber being cooled, lowering the efficiency of the overall cooling system.

Mounted "downstream" in an exhaust capacity, the fan does not contribute any heat rise to the temperature of the cooling air. However, in this location the fan motor is flushed by an airstream which is higher in temperature by the amount of the heat rise imparted to the air in passing through the area being exhausted. This point must be considered in connection with the allowable motor-winding temperature rise. The motor and blower may be mounted on the inside of the cabinet and the air pulled in to keep the cabinet under a slight overpressure. By using a filtered intake port in conjunction with this type of blower mounting location, the accumulation of dust can be greatly minimized.

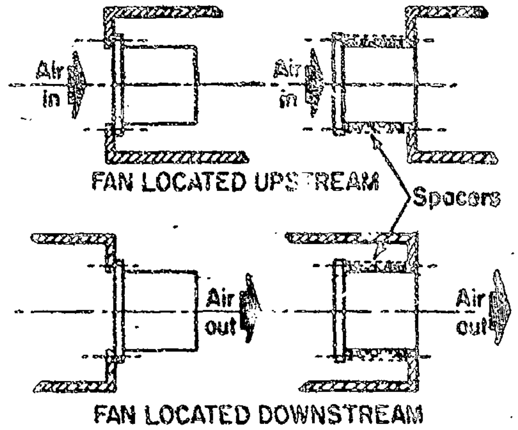


Fig. 7-13. Fan locations in air stream.

GENERAL CONSIDERATIONS

Constant or Limited Altitude. No serious design problems arise in the use of blowers for equipment operating over a limited range of altitude. Because the rate at which heat is generated in the equipment is constant, regardless of the altitude at which it is operated, the problem at constant altitude is one of calculating the volume of air at ambient temperature required to perform the cooling process.

However, if the altitude range is great, say from sea level to 70,000 feet or higher, the design and control of cooling systems, including that of forced air movement, becomes more complex. If the capacity of the air movement portion of the cooling system is inadequate, overheating is certain to occur at the higher altitudes if the equipment is operated at full rating in power and time. On the other hand, if there is inadequate control of the air moving system, at sea level more air flow than needed is provided with resultant excess power consumption (and heat dissipation) by the blowers and decreased efficiency.

It is apparent that the worst condition is the one to be prepared for with sufficient control of the air supply system so that under more favorable conditions the rate of flow can be decreased. The control system must also be able to compensate for varying atmospheric air temperature.

In designing a cooling system to operate at appreciable altitude, the quantities and values used in making calculations for a system which is to function at sea level atmosphere must be modified. This is necessary to allow for the

change in air density (weight per volume) which decreases rapidly with increasing altitude (see Fig. 7-14). Accordingly, in applications where the weight of air is a measure of effectiveness, the additional air volume required at high altitudes must be provided.

Due to the decrease in density, the volume of air required for constant weight delivery at 60,000 feet (assuming constant air temperature) is 15 times that required at sea level. It is expected that an aircraft cycling in altitude will encounter a random series of varying air densities. Under such conditions, utilizing an air reservoir of such inconstancy, it is clear that a constant-speed fan will not achieve uniform efficiency in moving volumes of air by weight. For this reason, either series motors are used in high-altitude applications because of their inverse relationship between running speed and shaft load, or barometric switches are employed to change motor-operating conditions to increase the air flow in inverse relation with air density to maintain constant movement of air by weight.

Frequency Considerations. Variable frequency blowers are available which will operate at minimum loss of power over the complete range of frequencies encountered in aircraft power supplies (from 320 to 1000 cps).

Although the wide variation would normally cause large swings in speed and cfm output, this type of blower will provide a substantially uniform output of air at atmospheric pressure. At high altitude, the speed will increase, providing additional volume of cooling air.

Heat Exchanger Systems. Within recent years the whole problem of reducing the operating temperature of electronic equipment

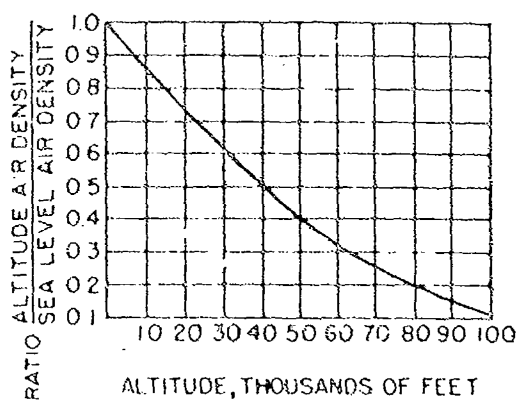


Fig. 7-14. Atmospheric altitude-density relationship.

has been studied quite thoroughly, and the literature is already rather extensive. The design of heat exchanger systems, the use of ducting, shields, heat sinks and so forth, are not considered here.

Constant Air Flow Vs. Constant Surface Temperature. In calculating and designing the air-flow system, the engineer has three basic methods or bases: (1) constant surface temperature, (2) constant weight flow of air, and (3) constant air discharge temperature.

The Ohio State report indicates that constant air flow at increased altitude is not only unnecessary to maintain constant cooling capacity but that it is undesirable. (1) It has one outstanding characteristic in that it provides for the utmost safety in temperature since the maximum surface temperature would occur at sea level. The pressure drop of a particular system described in the Ohio State report would be 194 percent greater at 70,000 feet than for a constant-discharge-temperature system, and the blower power required would be 450 percent greater. Blowers for constant-surface temperature or constant-discharge temperature would not differ very greatly in size.

Blower Control

Where the equipment must operate under varying conditions of altitude or ambient air temperature, some means of controlling the flow of cooling air is necessary. For example, it may be desirable to restrict the volume of air flushed through an enclosure to that which will maintain the required temperature rise limitations. Occasionally conditions have been found in which intermittent operation of a fan or blower has been adequate for cooling an enclosure; for example, when the ambient temperature or the dissipated load vary greatly. The hottest location within the enclosure should be selected for the installation of a thermostatic control element which will close the blower input power circuit when the ambient temperature reaches an arbitrarily imposed upper limit.

Airflow Interlock. Where the safety of equipment is dependent upon continuity of airflow, the equipment engineer may justifiably call for the incorporation of an air-interlocking control element to guard against complete absence of air or against a reduction in the volume of air below a safe minimum. Reduction in the volume of cooling air may result from pollution of dust filters or of heat exchanger radiators, clogging of finned-anode transmitting tube shields, partial loss of

power in a three-phase system, loose boots, clamps or flanges in air ducts, and so on.

A selection may be made between static pressure or air velocity to provide actuation of the device. Where duct work is used in a cooling system, either a static pressure or a velocity-operated device may be used. The velocity-operated unit is preferred in this situation since the static pressure element will not give protection in case of clogging of the air circuits upstream of the device.

To select a velocity-operated switch of a proper rating for its application, the velocity of the air at the intended location of the switch must be established. It is possible to determine this quantity by actual measurement, by calculation where other parameters are known, or by estimation where experience makes this possible.

To measure the air velocity, a Pitot tube, a hot-wire anemometer, or other similar devices can be held in the airstream at the exact point where the vane of the switch will ultimately be located and the air velocity read from this device.

If the cfm delivery of the fan or blower is known or can be estimated with appreciable accuracy, the air velocity in a duct at the point of switch insertion can be calculated. The cubic-feet-per-minute (cfm) figure of air which passes through the duct is a volume figure and should not be confused with the feet per minute which is a velocity figure. The relationship is

$$\text{Velocity (feet per minute)} = \frac{\text{cfm}}{\text{Area of duct (sq ft)}}$$

Whenever a velocity-operated air switch is to be operated in an airstream consisting of nonstandard air (departure from sea level atmosphere), the sensitivity of the switch will have to be adjusted to compensate for the air-density gradient.

Axial Blower Control. For applications of large cooling capacity to be operated only at constant altitude and for long flight duration, use of an axial-flow blower may be justifiable. The control problem would not exist, the unit would operate at the design point only, and the inherent high efficiency of the unit would result in weight and space savings. However, if highly variable flight conditions are to be considered, provisions for control must be made that could not easily be met with an axial-flow unit. Operation at infinitely variable speed may be feasible to a limited extent, but large variations in efficiency and instability because of pulsation could hardly be avoided. Control by throttling is only feasible over a very narrow range because pulsation is usually encountered when the discharge volume is reduced 10 to 15 percent below the design point. Control by bleeding is impractical because of its inherently poor economy and because the efficiency decreases rapidly as the discharge volume is increased a few percent above the design point.

Study of the possibilities of controlling the operation of axial-flow units by means of varying the angle of the stator and rotor vanes indicated that the greatest effect on extending the control range can be obtained by adjusting the rotor vanes. The use of variable vane setting affects the efficiency but not to the same extent as does speed variation. It can be shown that adjustment of the rotor vanes over an angular range of 20 to 30 degrees and use of four operating speeds would allow operation under stable conditions from sea level to 70,000 feet altitude, while meeting the air pressure and volume requirements of the cooling system. A machine of extremely complicated design would result, which does not appear at all practical in terms of a blower for systems with less than 10-kw cooling capacity. In contrast, variation of the stator vane angles is mechanically considerably simpler but relatively ineffective and would probably not satisfy the control requirements even when used in conjunction with considerable speed variation.

Centrifugal Blower Control. For most applications of blowers in the cooling of electronic components, the primary requirement is the control of pressure production and flow volume. In general, the power requirements for present cooling problems are of sufficiently low order of magnitude that extreme emphasis on efficiency does not seem to be pertinent. Inasmuch as it is necessary to control the blower to meet the cooling requirements, a blower that provides for the maximum in control is preferred over a blower with less control but high operating efficiency. For this reason, centrifugal blowers should be contemplated for use with electronic equipment over wide ranges of altitude.

Numerous possible methods of controlling the flow of cooling air are discussed in the Ohio State report. They include variable-speed

motors, variable-vane width (angle), bleeding, throttling, and others.

GENERAL CONCLUSIONS

Certain general conclusions were reached as a result of the study at Ohio State. They are:

1. Centrifugal blowers are best suited for use in the cooling of electronic units over wide ranges of altitude because they are more adaptable to a wide range of control.

2. From the standpoint of minimum power requirements, small blower dimensions and moderate operating speed, heat dissipating systems should be so designed as to obtain low-pressure drops that should preferably not exceed 1.0 inch of water at sea level. Cooling by the use of large air volume with limited temperature rise is preferable to cooling with smaller air quantities and larger temperature rises.

3. Blowers for use with air cooling systems are feasible at 70,000 feet. The power requirements at this altitude will be 3-1/2 times as great as required at 60,000 feet and 7-1/2 times as great as necessary at 50,000 feet. Power requirements at 70,000 feet could be held to within 0.5 hp per kw cooling capacity provided that systems with sea-level pressure drops in the order of 0.5 inch of water are utilized.

4. For best blower proportions, the use of high design speeds is primarily desirable for systems of high pressure drop or systems of moderate pressure drop with small capacity. Blowers designed for units with moderate pressure drop and of appreciable heat dissipation capacity in the order of 3 to 5 kw would be best designed for operation between 18,000 and 15,000 rpm for maximum altitudes of 70,000 feet.

5. For smallest diameters and best proportioned impellers, blowers of large cooling capacity are undesirable. By using increased operating speed with increasing design altitude, the impeller diameters of blower units with cooling capacities in the order of 1 kw could be held between 4 and 5 inches. Increased cooling capacity requires larger diameters not because of greater pressure requirements but because of the necessity of reducing the operating speed to maintain impeller proportions so that the width does not become unreasonably large.

6. Most favorable control for operation over wide changes in altitude is by infinite-variable speed. Step-wise control alone makes the maintenance of constant equipment temperatures impossible. Step-wise speed variation with bleeding of air causes excessive power requirements. Step-wise speed variation with throttling is feasible over limited ranges of altitude but requires excessive motor power at the extreme altitudes. Limited width variation with step-wise speed control and throttling combined is favorable from the standpoint of power consumption as well as the relative simplicity of the method.

7. The range of speed variation from 70,000 feet altitude to sea level is in the order of 11 to 1; from 50,000 feet to sea level, a speed range of about 4 to 1 should be feasible.

DRIVE MOTORS

Electric motors are used predominantly in air-cooling techniques for electronic equipment because they are clean, economical, small in size, and further, because they deliver acceptable values of horsepower per unit of weight.

The selection of a motor to drive an impeller should be based on the nature of the power source to be utilized, the needed horsepower delivery, shaft speed and direction of rotation, and weight and physical dimensions. Additional considerations concern mounting methods and details, maintenance requirements, and accessibility in performing the typical maintenance schedule. Motor life and ease of replacement are prime points to be investigated, as well as availability and interchangeability of parts. The range and nature of anticipated operating environments should be weighed in the selection of the drive motor in proportion to their potential influence on operating stability.

A wide variety of motors is available and the design engineer who may have to specify such a motor will have no difficulty in finding numerous examples which will do the job he has in mind. Operating characteristics and performance figures are readily available from numerous manufacturers.

D-C Motors

For most applications, d-c motors of the shunt-wound or compound-wound types are used. In the smaller sizes (approximately 1/20 hp and below), shunt-wound motors are standard, whereas the larger motors are

compound wound. The series-wound motor is used where its varying speed characteristic and high no-load speed are desirable. It develops a high starting torque but has a limited output at the higher speeds. Remember that a d-c motor uses brushes and may be unsatisfactory in applications which cannot tolerate electrical noise or in volatile or explosive environments which might be jeopardized through the generation of electrical sparking.

Motors are available in finned cases which dissipate heat readily, thereby maintaining low winding-temperature rises. In "upstream" installations, the motor temperature rise is held down by the intake airflow, but is passed on to the chamber to be cooled. In "downstream" locations, the fan winding temperature is increased by the warm exhaust airflow, and this condition may require a special motor featuring a low winding-temperature rise characteristic.

D-C motors are available in 6-, 12-, 24- to 28-, 105- to 125-, and 230-volt types and provide a very wide selection of horsepower ranges.

A-C Single-Phase Motors

Single-phase motors are available in a variety of types (see Fig. 7-15). Practically all operate as squirrel-cage induction motors. Since a single-phase induction motor does not develop any starting torque, it must be provided with an auxiliary starting-winding or phase-shifting device. The essential difference between the various types of single-phase motors lies in the type of starting-winding or phase-shifting device employed.

Series-Wound Motors. The series-wound single-phase motor is similar in construction and principle of operation to the series-wound d-c motor. It employs a stationary field winding and a commutated rotor (armature winding), the two connected in series. Like the series d-c motor, its speed increases as the load decreases. Useful load speeds range from 5000 to 10,000 rpm; no-load speeds range from 150 to 300 percent of full-load speeds. The principal advantages of series motors are their extreme compactness and light weight in relation to the power delivered. These motors are available for operation at all single-phase line voltages and at frequencies of 50, 60, and 320 to 1000 cycles. This type of motor has the same disadvantages as the d-c series-wound motor with respect to electrical noise. Because of its commutated armature, avoid using the series-wound single-phase motor in explosive environments and in atmospheres contaminating to the commutator material. Maintenance requirements call for replacement of brushes, cleaning of commutator, and occasional lubrication.

Shaded-Pole Motors. Shaded-pole motors feature a squirrel-cage rotor winding and a concentrically-wound single-phase stator winding. A portion of each stator pole is "shaded" by a single turn of heavy copper wire. Current out of phase with the current in the main winding is induced in the shading coil. A revolving magnetic field results, similar to that of a polyphase induction motor, and starting torque is developed. Motors of this type are inefficient and have low starting torque. However, in small sizes they are the most economical design. They are used in ratings up to about 1/25 hp for small fans. The shaded-pole motor is used where low-temperature starting or high starting torque are not important. These motors require no centrifugal-type starting switch since the shading coils in the stator produce a rotating field for starting. The speed regulation is on the order of 15 percent and the efficiency is lower than that of the split phase of the capacitor-start motor. The shaded-pole motor is not reversible except with special design. Since this type of motor has no commutator or brushes, maintenance is simplified.

Split-Phase Induction Motors. Split-phase induction motors have squirrel-cage rotors and two-phase stators with one of the phases wound for relatively high resistance. Since the ratios of resistance to reactance of the two phases are not equal, the currents in the windings are not of the same time-phase, but approach the relations of a true two-phase motor. Hence, a revolving magnetic field is produced and torque is developed. The high-resistance winding, because of its high losses, must be disconnected before the motor gets up to speed. The disconnecting switch usually is operated by a centrifugal mechanism on the rotor at 75 percent of nominal speed. From that point, acceleration continues on up to normal speed. These motors are suitable for starting at low temperatures and are not reversible without stopping, except with special design. Speed regulation is good (about 3 to 6 percent), which is a characteristic of all squirrel-cage induction motors. Special designs can be had with somewhat more starting torque at some loss in efficiency, power factor, or speed regulation. These motors are used in ratings from 1/50 to 1/3 hp.

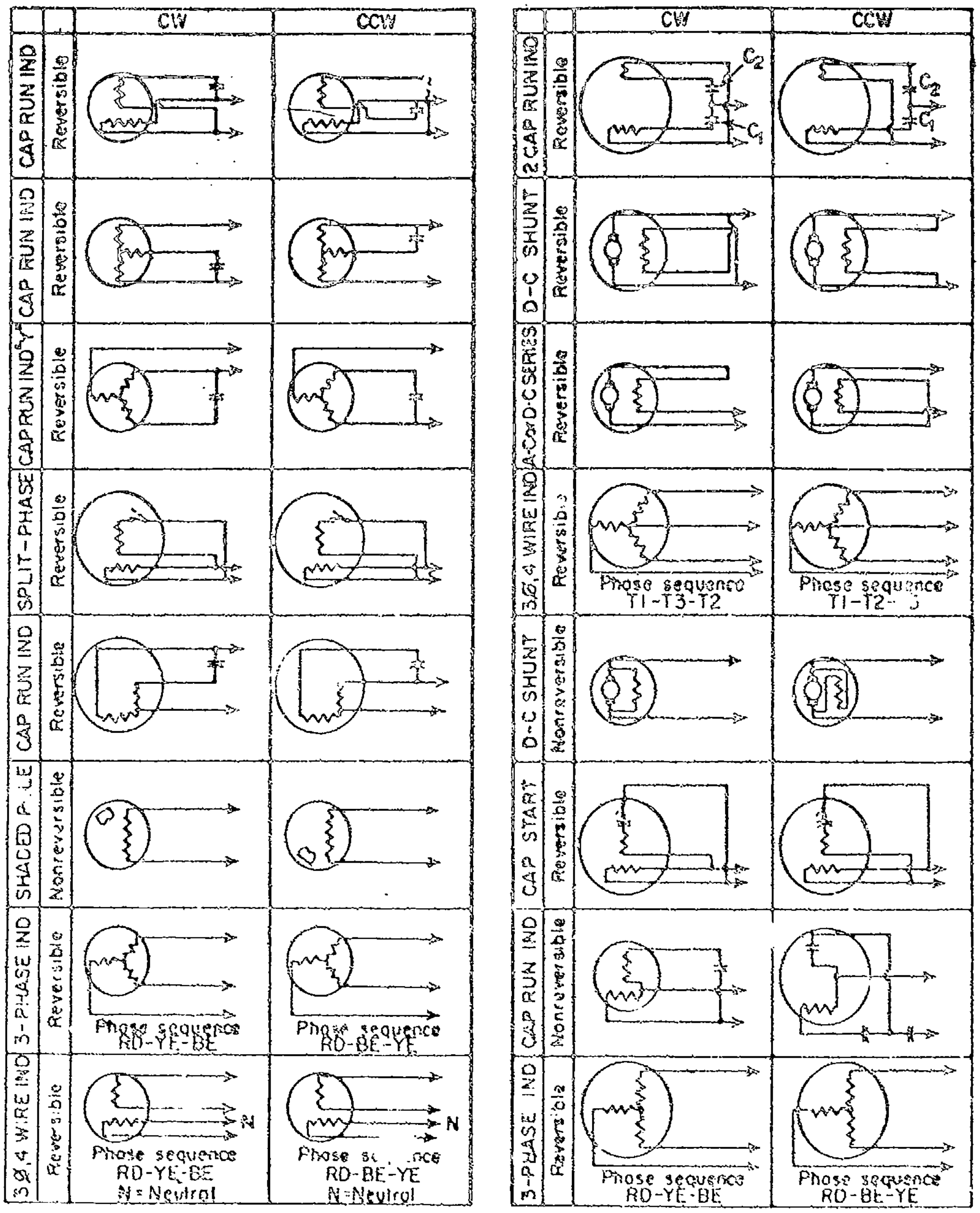


Fig 7-13. Single-voltage motors, wiring connections.

Capacitor Motors. Capacitor motors fall into three categories: capacitor-start, split-capacitor, and two-value capacitor motors.

1. The capacitor-start motor has a squirrel-cage rotor and a main winding and an auxiliary winding on the stator. A capacitor (frequently mounted on top of the motor) is connected in series with the auxiliary winding to provide the necessary phase shift of the current flowing through it. Since the capacitor is rated for intermittent service only, it must be disconnected for normal operation, usually by a centrifugal mechanism on the rotor. At low temperatures, the starting capacitor exhibits the characteristics of a high resistance and, unless the capacitor is mounted in a separate, heated space, the motor loses its quick-starting characteristics below about 0 C. The motor is not reversible while running, except

by special design. Capacitor-start motors are available in ratings from 1/6 to 1 hp.

2. The split-capacitor motor is somewhat similar to the capacitor-start motor except that the capacitor connected in series with the auxiliary winding is rated for continuous operation and is left in the circuit, running as well as starting. Furthermore, the capacitor is selected to give best operation (maximum efficiency and minimum noise and vibration), at full speed at a sacrifice in starting characteristics. As a result, these motors develop only 40 to 60 percent starting torque and can be applied only to easily started loads such as direct-connected fans and blowers. Two-speed or adjustable-speed operation of fans and blowers is often provided by controllers that vary the voltage impressed on the motor (see Fig. 7-16).

3. The two-value capacitor motor uses different values of effective capacitance in series with the auxiliary winding during running and starting. It usually has a continuously-rated capacitor that remains in the circuit during starting and running, and an intermittently-rated capacitor that is in the circuit during starting only. Therefore, the motor has a high starting torque as well as good running characteristics.

Synchronous Motors. Synchronous motors in the small-power sizes usually are built as reluctance motors. The stators are similar to those of single-phase induction motors and may be of the shaded-pole, split-phase, or capacitor type. The rotor has a squirrel-cage winding and the core is shaped to provide projections (salient poles) corresponding to the number of poles for which the stator is wound. The motor starts as an induction motor, but after reaching a speed near synchronism, it pulls into step because of the salient poles, and operates exactly at synchronous speed. Unlike the large-power synchronous motor which has a field winding on the rotor supplied with d-c excitation and which operates with unity or leading power factor with high efficiency, the reluctance motor operates at lagging power factor and has a rather low efficiency. Therefore, it is only used where exact synchronous speed is desirable.

Another type of synchronous motor available in the small sizes is the hysteresis motor. Its construction is similar to that of the reluctance motor except that the rotor is perfectly cylindrical and does not have a squirrel-cage winding. Its operation depends upon the permanent magnetism induced in the rotor by the magnetic field of the stator. It develops a constant torque from zero to synchronous speed. The fact that neither airborne nor ground military power sources necessarily have frequency stabilization should be remembered by the designer when synchronous motors of the reluctance type are empower. With varying frequency, synchronous speed is not necessarily constant speed.

A-C Polyphase Motors

In the small-power field, polyphase squirrel-cage induction motors meet the requirements of practically all applications. They develop a high starting torque with a starting current well within the limits of polyphase systems. Their efficiencies are slightly higher than those of single-phase motors. Polyphase motors are generally available in sizes of 1/6 hp and larger at 110, 220, 440, and 550 volts. This type of motor requires the smallest frame size for a given horsepower. Motors may be selected for operation from 50-, 60-, and 400-cycle power sources. They require little or no maintenance. Polyphase synchronous motors of the reluctance type are employed when exact synchronous speed is required, provided the power source is frequency stabilized. They are similar to the single-phase motors of this type except that no starting-winding or phase-splitting device is necessary.

Universal Motors

Universal-type motors operate from single-phase a-c or from d-c power sources. All are of the series-wound type, with a field winding on the stator connected in series with a commutated winding on the rotor. The straight series-wound rotor has a salient-pole field winding on the stator. The compensated series-wound motor has a distributed winding arranged in slots around the periphery of the stator. The latter has the advantages of better speed regulation and commutation and higher starting torque; the former is simpler in construction and more easily ventilated. Generally, the straight series-wound motor is used in sizes up to approximately 1/3 hp and the compensated series-wound motor is employed in the larger sizes. Typical full-load speeds are from 5000 to 10,000 rpm with no-load speeds ranging from 12,000 to 18,000 rpm.

Temperature Ratings

The allowable rise of small-power motors (measured by thermometer) is 40 C for general-purpose, open-type motors, and 55 C for

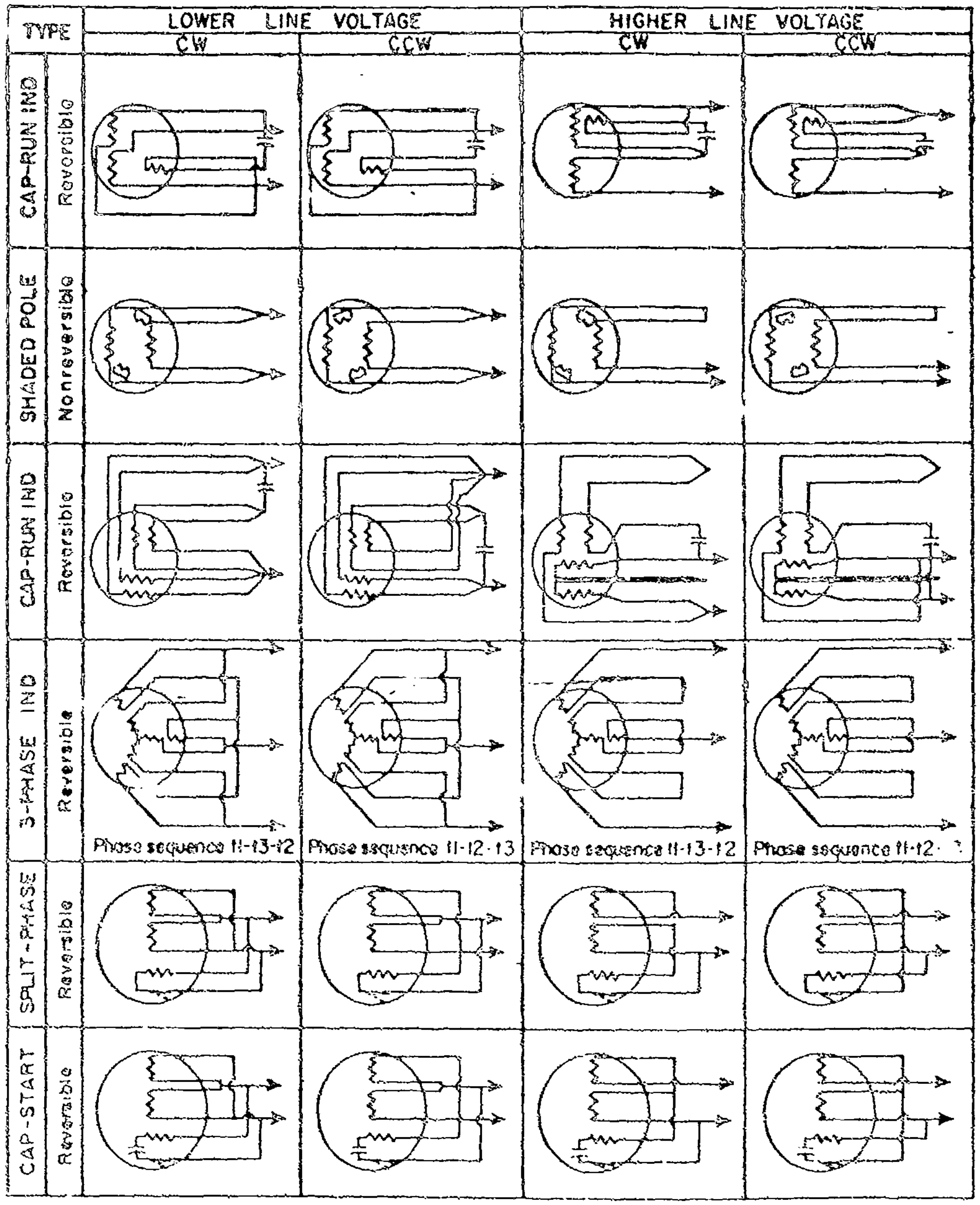


Fig. 7-16. Wiring connections of dual-voltage a-c motors for clockwise (cw) or counterclockwise (ccw) rotation.

special-purpose types (dripproof and such varieties). These figures denote the increase in temperature which will not be exceeded when the motor carries its rated load continuously (or for a specified time in the case of short-time-rated motors).

Temperature-rise ratings are usually made on the basis of normal ventilation, an altitude of not more than 1000 meters (3300 feet) and an ambient temperature of 40 C. At higher altitudes, less effective dissipation of heat causes a higher motor temperature rise. This rise assumes appreciable value about 3300 feet, and from that point increases at a rate which can be approximated as of 1 percent of ambient at sea level for each additional 330-foot increment of altitude. Ex-

pressed as an equation, this appears as

$$t_h = \frac{t_o}{1.1 - (h/33,000)}$$

where

t_h = temperature rise at altitude h
t_o = temperature rise at sea level
h = altitude in feet

Thus, a motor having a temperature rise of 40 C at sea level will have, at 9900 feet, a temperature rise of

$$t_h = \frac{40}{1.1 - (9900/33,000)} = 50\ C$$

The allowable temperature rise is determined primarily from the type of insulation utilized in the motor construction. Class A insulation has an upper temperature limit of 105 C. Operation in excess of this temperature may cause extensive damage to the motor. In Class B insulation, the upper temperature limit is fixed at 125 C. Class A insulation is standard for most types of motors, and Class B can be had at increased cost.

Motor Insulations

Class A: (1) Cotton, silk, paper, and similar organic materials when either impregnated or immersed in liquid dielectric, (2) molded and laminated materials with cellulose filler, phenolic resins, and other resins of similar properties, (3) films and sheets of cellulose acetate and other cellulose derivatives of similar properties, and (4) varnishes (enamel) as applied to conductors. The top allowable temperature for Class A insulation is 105 C. Some Class A insulations are undesirable for military applications. For instance, MIL-E-5400 prohibits the use of paper.

Class B: Inorganic materials such as mica and asbestos in built-up form, combined with binding substances. If Class A material is used in small quantities in conjunction with Class B, for structural purposes only, the combined material may be considered Class B, provided the electrical and mechanical properties of the insulated winding are not impaired by the application of the temperature permitted for Class B material. (The word "impair" is used here in the sense of causing any change that could disqualify the insulating material for continuous service.) The maximum allowable temperature for Class B insulation is 125 C.

Class C: Inorganic materials such as pure mica, porcelain, quartz, and similar materials. The maximum allowable temperature for Class C insulation is 150 C.

Class H: (1) Mica, asbestos, glass fiber, and similar inorganic materials in built-up form with binding substances composed of silicone compounds, or materials with equivalent properties, and (2) silicone compounds in rubbery or resinous forms or materials with equivalent properties. A minute proportion of Class A materials may be used only where essential for structural purposes during manufacture, providing the electrical and mechanical properties of the insulated winding are not impaired by the application of the temperature permitted for Class H material. The peak allowable temperature for Class H insulation is 180 C.

Class O: Cotton, silk, paper, and similar organic materials when neither impregnated nor oil-immersed. The maximum allowable temperature for Class O insulation is 90 C.

Motor Speed Characteristics

Motors are classified according to their speed characteristics as follows:

1. Constant speed. A constant speed motor exhibits no appreciable change in speed with variation in load.

2. Varying speed. A varying speed motor possesses inversely related speed-load characteristics, that is, speed decreases with increasing load.

3. Adjustable speed. An adjustable speed motor permits speed control over a fairly broad range. A change in load has no effect on speed once set.

4. Adjustable varying speed. An adjustable varying speed motor is one in which the speed can be varied over a fairly broad range. Once speed has been adjusted, it is subject to variation due to a change in load.

5. Multispeed. A multispeed motor has several different speeds, each selected by connected poles in a specific electrical combination.

Motor Torque

The full-load torque of a motor is established by its horsepower and speed rating as follows:

$$\text{Full-load torque} = 5250 \times \frac{\text{horsepower}}{\text{rpm}} \text{ (in lb-ft)}$$

The various torques associated with motor performance are defined as follows:

1. Starting torque of a motor is the torque developed at zero speed. In a-c motors it is the minimum torque for all angular positions of the rotor, with rated voltage and frequency applied to the motor.

2. Pull-up torque is the minimum external torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs. For motors that do not have a definite breakdown, the pull-up torque is the minimum torque developed up to a rated speed.

3. Rated breakdown torque of an a-c motor is the torque the motor will carry with rated voltage and frequency without an abrupt drop in speed. It indicates the peak load the motor can carry without stalling or decelerating to a lower speed.

4. Pull-in torque of a synchronous motor is the maximum constant torque under which the motor will pull its connected inertia load into synchronism, at rated voltage and frequency, when its field excitation is applied.

5. Pull-out torque of a synchronous motor is the maximum sustained torque the motor will develop at synchronous speed for one minute, with rated voltage, rated frequency, and normal excitation.

Shaft-Speed Limitations

When induction motors are used, the maximum obtainable shaft speed is 3450 rpm for 60 cps, and 2875 rpm for 50 cps. For 400 cps, there is generally a choice between approximately 3700 rpm, 5400 rpm, 7200 rpm, 10,500 rpm and 21,000 rpm. If a commutator-type motor is used, either a-c or d-c, the maximum shaft speed is roughly 10,000 rpm for "miniature" motors and roughly 5000 rpm for small motors of below 1/20 hp. Commutator-type motors are generally avoided because of appreciable maintenance requirements.

Electrical Noise

Commutator-type motors, either a-c or d-c, are a constant source of sparking while in operation. Such sparking creates electrical interference of an intensity depending upon the magnitude of voltage and current involved. The electrical noise thus produced may be periodic or aperiodic in nature, and may vary over a very broad frequency band. This radiation may jeopardize the efficient operation of electronic equipment at varying distances from the source. For example, impulse-operated coding equipment and computers may be triggered by false commands in a random pattern by such radiation. When this problem arises, the solution involves shielding or suppression, or both.

Enclosures

Electric motors are available in various kinds of enclosures for use in various operating and environmental conditions. An open-type motor is one in which no resistance is presented to the flow of ventilating air by the motor other than that necessitated by mechanical construction. A totally enclosed motor is defined as one which permits no free exchange of air between the inside and outside of the case. This is not meant to imply that the case is airtight, but that it is sufficiently sealed to protect the motor from dirt, moisture, chemical fumes, or other harmful atmospheric ingredients. A totally enclosed fan-cooled motor is equipped for exterior cooling by a fan or fans integral with the motor, but external to the enclosing parts. A protected motor is one in which all vents in the motor case are protected by a metal screen or perforated shield to prevent accidental contact with live or rotating parts within the case.

A dripproof motor is one in which the ventilated openings are so constructed that drops of liquid or solid particles falling on the motor at any angle not greater than 15 degrees from the vertical cannot enter the motor either directly or by striking and running along a horizontal or inwardly inclined surface. A splashproof motor is one in which the ventilating openings are so constructed that drops of liquid or solid particles falling on the machine or coming towards it in a straight line at any angle not greater than 100 degrees from the vertical cannot enter the machine either directly or by striking and running along a surface. An explosion-proof motor is one in an enclosing case designed and constructed to withstand an explo-

sion of a specified gas or dust that may occur within it and to prevent the ignition of the specified gas or dust surrounding the motor by sparks, flashes, or explosions that may occur within the motor case.

Mounting

Blower-motor combinations are available which mount directly against the bottom, side, or top of the enclosure to be cooled. To minimize transmission of any residual vibration from motor or propeller to the mounting support, numerous vibration isolation mounts may be procured which are specifically designed to accommodate a broad range of blower motor sizes and weights. Mounting spiders with nonstandard brackets facilitate and simplify mounting blower-motor assemblies of many shapes and configurations.

In mounting the blower, consideration should be given to efficiency in application, long life, freedom from vibration, and ready accessibility for maintenance, such as lubrication of the motor or replacement of the dust filter. Where sleeve bearings are used, horizontal positioning is generally preferable. Ball-bearings permit mounting in almost any position.

Dual Purpose Installations

Where space limitations and power supply become a problem, dual-purpose installations are sometimes used to drive blowers. In some instances, where dynamotors are used to power equipment, the dynamotor shaft carries a blower rotor or fan. One such installation has an axial fan on one end of the shaft for dynamotor cooling and an axial blower on the other end for equipment cooling. A more compact and more efficient installation results.

FILTERS

Although forced-air flushing of equipment to maintain control over the operating temperature can contribute greatly to the reliability of the equipment, it can also defeat its purpose if the source of air conta[illegible] contaminating agents of an abrasive, erosive, or electrically conductive nature. When the air source is contaminated, filters are necessary to prevent the entrance of such agents into the equipment. Filters used with fans and blowers may be of the integral type which form a part of the blower unit, or may be of the type that can be removed and replaced quickly and easily.

Two types are commercially available: the dry filter and the viscous filter (see Fig. 7-17). Dry filters are generally of the throw-away variety and are composed of activated carbon, cloth, spun glass, hair, or a cellulose material. Certain classes of filters can be cleaned and some re-use is practical; other filters must be discarded when pollution accumulates to a point which makes subsequent usage impractical.

Viscous filters make use of the properties of oil in capturing particles of dust. Common practice is to form the filter medium in graded densities so that the coarser material is located on the inlet side of the filter. This is usually made of the metal fibers. In this way, the larger dust particles will lodge at

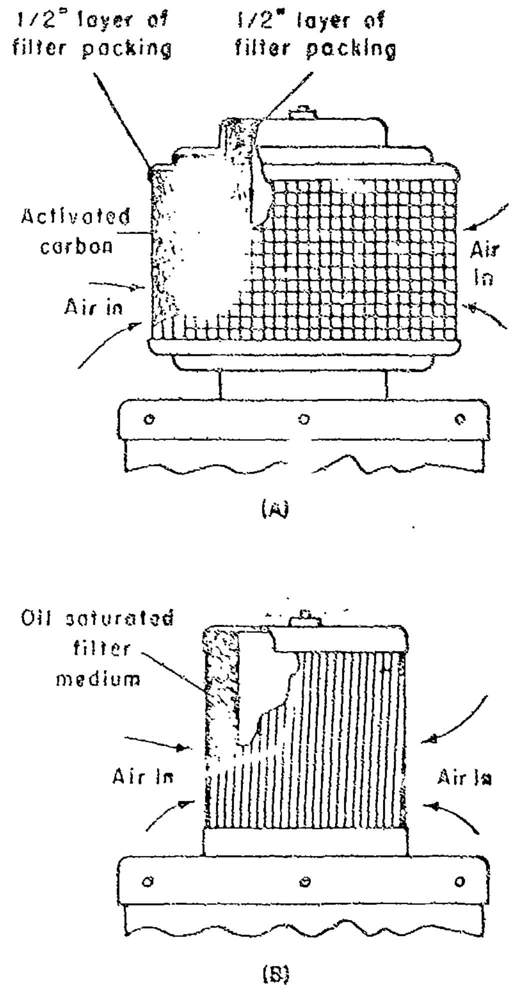


Fig. 7-17. Blower filters: (A) Dry type using activated carbon, (B) Viscous type using oil-saturated filter medium.

this point and may be more easily removed. In some viscous filters the filter packing material may be removed and replaced with clean packing of an identical type.

Filters are most frequently mounted at the air-intake port as an integral part of the blower-motor unit, although it is not uncommon to find filters located at equipment air exit ports as well. A filter is used at an exit port when dust must be excluded from a cabinet area that is not maintained under pressurization. Pressurizing alone is a good means of keeping out dust.

The selection of a dust filter is influenced by (1) the nature of the dust, (2) the dust concentration, and (3) the degree of maintenance ease provided for cleaning or replacing the filter.

Air Resistance

The efficiency of a filter to trap dust decreases with increasing velocity of the air through the filter. Similarly, the air resistance, or back pressure, which a filter introduces in the air stream increases approximately as the square of the air velocity. It will decrease approximately as the square of the filter area. The air resistance presented by the filter will increase almost directly as its thickness.

Filter Area

To be most successful, the filter area should be as large as conditions will permit. This increases the dust-catching ability, decreases the required frequency of filter replacement, and decreases the pressure drop over the filter. In the case of a propeller fan, decreased back pressure will result in a quieter fan and possibly allow the choice of a propeller with a lower pitch, which also reduces noise. The blower intake should be fairly evenly distributed over the filter area, either by the use of an appropriate inlet cone or by allowing sufficient space in a filter box behind the filter for the air to even out over the filter area. The use of inlet cones is recommended whenever the blower-inlet velocity is high. In this case, their usage reduces "entrance losses" at the blower intake. These losses are comparable to impedance mismatching in electronic circuitry.

Pressure Drop

In a high-pressure system, the pressure drop over the filter is a relatively small percentage of the total pressure drop on the system. An increase of the back pressure over the filter due to pollution, therefore, can be expected to cause only a relatively small decrease in the volume of circulating cool air. In a low-pressure system, the pressure drop over the filter may be a large percentage of the total pressure generated by the fan or blower. For example, a centrifugal blower cooling a compartmented radar receiver may generate from 2- to 6-inch static pressure. In this case, a 0.3- to 0.5-inch static pressure drop over the filter is then considered a small percentage. However, if it is a propeller fan which flushes a cabinet, the filter is generally the major restriction to the airflow and almost the entire pressure-building capacity of the fan is applied to overcome the dust filter resistance.

In relation to their size and power propeller fans move large volumes of air but are expected to work against low back pressures only. In such applications, filters of high area and low density are required to minimize the pressure drop due to the filter.

Because the pressure drop increases approximately as the square of the velocity of the air through the filter, with increasing velocity a pressure loss is soon reached which constitutes a practical limit. Beyond this point so much extra pressure has to be generated by the fan or blower for overcoming the resistance of the dust filter that the extra cost (and noise) is not warranted by the saving in dust filter expense (expense of the dust filter as well as the added expense of cabinet space). "Capacity" figures given by filter manufacturers are generally based on a practical upper limit velocity of 300 ft/min. This figure is chosen with primary regard to dust-catching ability. Considerations of allowable back pressure may dictate a required lower velocity, notably in the case of propeller fans used to flush cubicles.

Pollution

With increasing pollution, the resistance of a dust filter increases, that is, the back pressure over the filter increases. The period of time (cubic-feet-hours) after which a dust filter is to be cleaned or replaced depends entirely on the condition of the air and may vary between great limits. The limits are determined by the quantity of air moved per unit time and the quality of the dirt per unit volume of air. Some types of dirt have a greater restraining action when caught in the

filter. Therefore, it is impossible to give an indication as to the number of hours of use after which a filter should be cleaned. Neither can this be judged safely from the exterior appearance of a filter.

Permanent-type filters can be cleaned by washing and relubrication. The replacement-type filters can be cleaned to some extent by vacuum cleaning. With this type, however, highest efficiency is maintained by replacement.

BLOWER MAINTENANCE

Maintenance problems should always be considered during selection of a blower-motor combination. Operation of electronic equipment in many cases depends on proper cooling. Because blower reliability is so highly important, a blower-motor combination requiring minimum maintenance may be preferable to a combination having the exact desired operating characteristics. In some cases, it may be necessary to alter blower requirements to fit an available blower with low-maintenance requirements. Easy maintenance is designed into an installation by selection of a low-maintenance blower-motor combination and designing its mounting to provide accessibility and adequate breathing space. Of particular interest from a maintenance point of view are bearings, brushes and switches, blower sections, and filters. When a blower-motor combination is being considered, the maintenance of these items should be important deciding points.

Bearings

A grease-packed sealed ball bearing requires no maintenance during its normal life. Motors with this type of bearing packed with proper grease to meet extreme operating conditions are readily available in the power range required for blower application. Simple a-c induction motors with sealed ball bearings regularly operate 6000 to 15,000 hours between overhauls. On the other hand, sleeve bearings require regular lubrication and are extremely sensitive to lack of lubrication. If a motor with a sleeve bearing is selected, the lubrication schedule specified by the manufacturer must be followed, and the installation design should provide accessibility to the lubrication points.

Brushes and Switches

Commutated motors have brushes, while certain inductance motors have automatic cut-out switches that control starting windings. In some installations there are starting relays. Each of these is a source of maintenance problems. Brushes and commutators are susceptible to insidious troubles that cause gradual loss of power output, excessive sparking, commutator gouging, and short circuits. Brushes must be periodically inspected for proper surface and wear to assure reliable operation of the blower installations. Similarly, automatic cut-out switches on inductive motors require periodic inspection. Malfunction of this switch causes excessive power consumption or failure of the blower motor to start. Both of these maintenance problems are eliminated by selection of a split-capacitor motor. Starting relays are susceptible to contact wear and sticking. Periodic maintenance should include inspection and servicing of contacts and adjustment of the relays.

Blower Section

Primary maintenance considerations in the blower section are accessibility for cleaning the blower impeller and maintaining the blower controls if any are used. Operational times between blower cleanings are largely determined by the overhaul period of the motor. In severe service, it may be necessary to clean the blower more often unless filters are used.

Filter Maintenance

Maintenance of filters is a matter of periodic cleaning or replacement as discussed under the filter section above.

MILITARY SPECIFICATIONS

Bureau of Ships Specification Electronic Equipment, Naval Ship and Shore: General Specification 16E4(Ships) covers the requirements applicable to design and construction of electronic equipment. Paragraph 3.11.2 Forced Air Cooling of this specification specifies, "Where forced air cooling is used, dust filters will be required. Filters shall be of the cleanable type capable of passing air at a face velocity of 600 feet per minute with an accompanying pressure drop across the filter not to exceed 0.195 inch water gage when filter is loaded with dirt to 0.021 pounds per square foot (face area). Dirt used for testing filter shall consist of 48 percent lint, 43 percent fly ash, and 9 percent lamp black. Filters shall be tested dry. Size and method of mounting shall be acceptable to the bureau concerned." Paragraph 3.3 Safety to Person-

nel covers protection measures necessary in design of electronic equipment. Under this, paragraph 3.3.7 Mechanical Protection specifies that, "Adequate provisions shall be made to protect personnel from injury due to moving parts---." Paragraph 3.7 covers radio frequency and low frequency interference (noise) limitations. In similar fashion, the general requirements for each type of installation are covered in other military general specifications.

A motor-blower combination that meets the general specification must further meet more detailed specifications. For instance, in a shipboard installation employing a vaneaxial fan of fractional horsepower and an a-c motor, MIL-M-17059(Ships) Motors, Alternating Current, Fractional HP (Shipboard Use), and MIL-F-18953(Ships) Fans, Vaneaxial and Tubeaxial, Fixed and Portable, entilation, Naval Shipboard would be two applicable specifications. These refer to other applicable specifications. MIL-F-18953(Ships) under "3.10 Type A, Vaneaxial Fixed"—specifies the requirements of the fan and the type of motor, bearings, and controls to be employed. For a 1/4-hp fan, a continuous duty, service A, 1/4-hp, ball bearing motor meeting the requirements of the procurement documents is specified. MIL-M-17059(Ships) specifies the basic requirements to be met by such a motor.

DO'S AND DON'T'S FOR BLOWER APPLICATIONS

1. Do not use commutator-type fan motors in volatile, combustible, or explosive atmospheres.

2. Do everything possible to prevent restriction of air flow through the chamber to be cooled.

3. Select axial-flow fans for maximum saving in weight, space, and power.

4. Design blowers into equipment as supply blowers, rather than as exhaust blowers, so that the blower is on the cold side of the heat exchanger.

5. When operation is anticipated between sea level and 50,000 feet, use either a multispeed blower or use several blowers or both.

6. Do not expect electric motors to operate on a wide range of frequencies such as 300 to 1000 cps unless they are specifically designed for this range. The maximum spread on nominal 400-cycle motors is 380 to 420 cycles. Low frequency power will tend to damage a motor, whereas high frequency power will tend to reduce the mechanical output.

REFERENCES

1. "Design and Control of Blowers for Uniform Cooling of Electronic Equipment from Sea Level to 70,000 feet Altitude," Report No. 33a, Contract No. W33-038-ac-14987, Ohio State University Research Foundation, 7 April 1950.
2. "Thermal Evaluation of Air-Cooled Electronic Equipment," AF Technical Report 6579 WADC, Contract No. W33-038-ac-14987, Ohio State University Research Foundation, September 1952.

BIBILIOGRAPHY

"A Guide Manual of Cooling Methods for Electronic Cooling," Report No. HF-710-D-16, Contract No. NObsr 49228 BuShips, Index No. NE-111611, Cornell Aeronautical Laboratory, Inc.

"Fan Engineering," Buffalo Forge Co., 1948.

"Forced-Air Crossflow Cooling of Electronic Units," Report No. 45 WADC, Contract No. W33-038ac-14987, Ohio State Research Foundation, February 19[illegible]

"Methods for the Ultimate Dissipation of Heat Originating With Airborne Electronic Equipment," AF Technical Report No. 6493 WADC, Ohio State University Research Foundation, March 1951.

Bulletin No. 10, National Association of Fan Manufacturers.

Bulletin FM-1955, National Electrical Manufacturers Association.

"Power's Handbook on Fans," McGraw-Hill Book Co., Inc., New York, October 1951.

Proceedings of the Conference on Cooling of Airborne Electronic Equipment held at Ohio State University, Bulletin 148, July 1952.

Contents

CHAPTER 8: R-F TRANSMISSION LINES AND WAVEGUIDES

Chapter 8

R-F TRANSMISSION LINES AND WAVEGUIDES

The purpose of this chapter is to acquaint the design engineer with the properties of transmission lines and waveguides so that he may specify and apply them with the greatest probability of success. Although their prime function is to conduct r-f energy from one place to another, they are also very useful as circuit elements and as matching devices for ensuring that power may be transmitted with the least loss.

GENERAL TYPES

Broadly speaking, there are two basic types of these power-transfer elements: transmission lines and waveguides.

Some of the characteristics and parameters possessed by both transmission lines and waveguides are treated first, then the detailed descriptions and applications of transmission lines are given, followed by the same type of material on waveguide. Finally, the effects of environment on both lines and guides will be found.

Transmission lines are of two broad and basic types, (1) the multiwire line, a characteristic form of which is the simple "twin-lead" used to connect a television antenna to the receiver, and (2) the coaxial type in which a central conductor is separated from an outer conductor by spacers (beads) or by a solid dielectric material.

Waveguides are single-conductor devices and resemble a metal pipe or tube through which energy can be transmitted provided the frequency is high enough compared to the cross section dimensions of the pipe. By an extension of the term, a waveguide may also consist of a dielectric rod or a wire coated with a dielectric.

GENERAL CHARACTERISTICS

When electrical energy is introduced to a line at one end, as from a generator, current flows through the conductors and a voltage appears across each portion of the lines. Electric and magnetic fields appear in the dielectric, which may be air, which separates the conductors. These fields have their lines of force at right angles to each other and at right angles to the direction of energy propagation down the line. Thus, the term "transverse electromagnetic wave" (TEM) describes the phenomenon. Other types of transmission may occur but the TEM mode is called the principal mode and only one TEM mode is possible on a two-conductor line. "Higher" modes can be supported by a single-conductor line; that is, by a waveguide, but a waveguide will not transmit power by a principal or TEM mode.

Transmission lines are employed for frequencies up to the general region of several thousand megacycles but the cross section dimensions become impractically small above this region. On the other hand, waveguide dimensions increase as the wavelength increases and become impractically large for transmission of frequencies lower than 1000 or 3000 Mc. Between 1000 and 10,000 Mc both lines and guides are employed. In a broad way, transmission lines may be thought of as low-pass filters; waveguides as high-pass filters.

In general, lines are smaller, lighter, and will conduct a wider band of frequencies than will waveguides. Waveguides have greater power handling ability, greater mechanical simplicity, and less attenuation. Table 8-1 summarizes pertinent data relating to three types of energy conductors.

STANDARDS

Of considerable practical interest to the design engineer is the high degree of standardization in this field as the result of close coordination between the military and commercial agencies. Although the early exploitation of waveguides was centered about military applications in World War II, many comparable commercial types of apparatus are now available in navigational radar, microwave relay links, television transmitters, and so forth. Wherever military and industrial standards exist, they are fully compatible for rigid lines, flexible coaxial cables, rectangular waveguides, and their related fittings. This has permitted further standardization in the area of microwave tubes, antennas, and test equipments. Much of the credit is due to the Army-Navy Radio Frequency Cable Coordinating Committee, which was active during the period from 1941 to 1950. Some of its functions were subsequently delegated to the Armed Services Electro-Standards Agency (ASESA). This Agency maintains an index of these items and distributes standards, specifications, and drawings for the parts contained therein. (1)

R-F TRANSMISSION LINES

Several basic parameters govern the application of transmission lines and must be considered in designing equipment in which they will be employed. These parameters arise from the fundamental properties of the lines as summarized below. (2,3,4,5)

Parameters

If a sine wave of voltage E_1 of frequency f is applied to one end of a very long line, a current I_x will appear in the line at distance x from the generator and a voltage E_x will appear across the line at the distance. These values of E_x and I_x are related to the initial voltage E_1 by

$$E_x = E_1 e^{-\gamma x}$$
$$I_x = \frac{E_1 e^{-\gamma x}}{Z_o} \qquad (1)$$

where e = 2.71828

In these expressions appear two of the important line parameters: Z_o, the characteristic or surge impedance of the line, and γ, the propagation constant. Both terms must be understood by the engineer and must be applied correctly.

It will be found, also, that the above values for E_x and I_x will be measured at point x even if the line is not infinitely long, provided it is terminated at the far end by a pure resistance equal to Z_o. Furthermore, if the line is so terminated, all of the energy sent down the line will be dissipated in this terminating resistor (neglecting any loss in the line itself). None of the energy will be reflected back to the source. Looking into the sending end of the line, one will see Z_o. This will not be true if the far-end load has any other value than Z_o. The sending-end impedance will have some value other than the characteristic impedance of the line if the load has a value other than Z_o.

The propagation constant γ is a complex quantity determined by the R, L, C, and the conductance G per unit length of line. Since it is a complex quantity, it can be expressed as

Table 8-1 Comparison of Transmission Lines for 5000 Mc*

Army-Navy Type No.	Rectangular waveguide	Rigid coaxial line	Flexible cable
	RG-49/U	RG-70/U	RG-9B/U
Outside dimensions	2 × 1 in.	5/8-in. dia	0.425-in. dia
Dielectric	Air	Air	Polyethylene
Weight, lb per ft	1.40	0.292	0.153
Attenuation, db per ft	0.011	0.035	0.23
Power rating	1.2 Mw	0.3 Mw	4 kv rms, max 60 watts

* Radio Engineering Handbook, 4th Edition, McGraw-Hill Book Co., New York, 1950.

$\gamma = \alpha + j\beta$ in which α is a measure of the attenuation of the line in nepers per unit length and β is the phase constant in radians per unit length. When α and β are multiplied by the number of the unit lengths of line being considered, the total attenuation and phase shift will be determined.

All of this discussion points to the fundamental fact that the voltage at any point x along an infinite or properly terminated line, compared to the initial voltage E_i, is lower in value (attenuated) by a factor $e^{-\alpha x}$ and retarded in phase compared to E_i by an angle βx.

Impedance

The surge or characteristic impedance, also called the iterative impedance, of practical lines (those with low series resistance and shunt leakage) is solely a function of the inductance and capacitance per unit length of line. Thus

$$Z_o = \sqrt{L/C} \tag{2}$$

Phase Constant

The complex propagation constant γ is made up of two factors, the attenuation constant α and the phase constant β, the latter often called the delay constant, wavelength constant, or phase-shift constant. Thus

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta \tag{3}$$

where

α = attenuation in nepers per unit length of line

β = phase constant in radians per unit length.

When α and β are multiplied by the number of the unit lengths of line being considered, the total attenuation and phase shift will be determined.

In an ideal line in which $R = G = 0$,

$$\alpha = 0 \tag{4}$$

and

$$\beta = \omega\sqrt{LC}$$

In a practical line,

$$\gamma = \sqrt{ZY} \tag{5}$$

where Z and Y are the series impedance and shunt impedance per unit length.

The phase delay and electrical length of a line are important factors in designing antenna feed systems, matching stubs, balancing networks, and timing circuits, and must be considered from the standpoint of magnetron "pulling."(6)

Line Length and Velocity

Consider a point x along the line where the phase has been retarded by 2π radians compared to the phase of the voltage (or current) at the generator end. The total phase shift, (the product of the shift per unit length of line and the length of the line) is $\beta x = 2\pi$ and since this distance along the line is one wavelength λ,

$$\beta\lambda = 2\pi \text{ or } \lambda = \frac{2\pi}{\beta} \tag{6}$$

As in any medium, the velocity of propagation is the distance traversed by any particular point of the wave in unit time, or

$$v = \frac{d}{T} = \frac{\lambda}{T} = \frac{2\pi}{\beta T} = \frac{2\pi f}{\beta} = \frac{\omega}{\beta} \tag{7}$$

where

$$\beta = \omega\sqrt{LC}$$

or

$$v = \frac{1}{\sqrt{LC}}$$

In free space, electromagnetic energy travels with the velocity of light. In lines and waveguides, the velocity of propagation is less than this figure but approaches it for open-wire air-dielectric lines. The general order of magnitude of the actual velocities are

Open-wire air-dielectric	= 0.93 to 0.97c
Beaded coax air-dielectric	= 0.79 to 0.99c
Solid dielectric	= 0.6 to 0.72c

where c = velocity of light.

Because the velocity of propagation is lower in practical lines than in free space, if a given phase retardation is required (for example the equivalent of one wavelength), then the actual physical line must be shorter than if the velocity were that of free space.

To determine the correct physical length of a line for a given purpose, it is common practice to calculate its length in feet from the relation λ, length in meters = $300/f_{Mc}$. This

will give the length if the velocity were equal to the speed of light.

This figure is multiplied by the actual velocity expressed as a fraction of the speed of light. Thus, one wavelength (electrical) of coaxial line having a velocity of propagation equal to 0.8 of the speed of light will be

$$\lambda \text{ length} = \frac{300}{f_{Mc}} \times 0.8 \text{ meter}$$

$$= \frac{984.3}{f_{Mc}} \times 0.8 \text{ foot}$$

$$= \frac{11,811}{f_{Mc}}$$

$$= 0.8 \text{ inch}$$

If the dielectric constant of the material separating the conductors is known, the velocity of propagation down the line may be found from

$$v = c/\sqrt{\epsilon}$$

where c = velocity of light
ϵ = dielectric constant, or relative permittivity

Table 8-2 compares the relative velocity (v/c) and the delay (1/v) for some of the more common dielectric materials and typical line constructions.

Note: At the higher frequencies, the so-called dielectric constant is not "constant" and it is becoming common practice to use the term "permittivity," in place of dielectric constant. Permittivity will be so employed in this chapter.

By making use of a low-frequency measurement of the capacitance of a unit length of the line and the fact that a half-wave of line, for example, will be shorter than a half-wave of free space, the impedance may be determined. Thus, if the physical line must be 0.8 as long as required in free space to produce half-wave resonance at a given frequency, the velocity of propagation v/c is 0.8 that of light. Then

$$Z_o = \frac{1016}{(v/c)\, C_{\mu\mu f/ft}} \qquad (8)$$

Attenuation

No practical line is free of losses; some attenuation will be experienced as a wave of current moves down the line. These losses limit the efficiency of any system of which the line is a part; and the losses limit the power handling ability of the line itself.

When the line constants are known and the attenuation is small, the attenuation can be computed from the real part of the propagation constant P. Thus

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}}$$

$$= \frac{R}{2Z_o} + \frac{GZ_o}{2} \text{ nepers per meter} \qquad (9)$$

The first of these terms represents the losses due to the conductors (α_c), and the second term represents the losses due to the dielectric (α_d). Certain correction factors must be added to these terms and these are discussed later.

GENERAL LINE PROPERTIES

Transmission lines have interesting and valuable properties. They may be employed as high-Q tuned circuits, as impedance matching or transforming devices, as delay lines, and for numerous purposes other than simple power transfer.

Table 8-2—Transmission Line Velocity and Delay

Dielectric construction	Weighted value ϵ	Relative velocity (v/c)	Delay time microseconds/ft (1/v)
Solid polyethylene	2.26	0.665	1.528×10^{-3}
Solid Teflon	2.10	0.690	1.472×10^{-3}
Helical Teflon support	1.23	0.901	1.128×10^{-3}
Teflon beads in rigid line	1.016	0.992	1.025×10^{-3}
Air or vacuum —no supports	1.000	1.000	1.016×10^{-3}

Open-Circuit Line. A lossless line of any length, open circuited at the far end, has an input impedance

$$Z_i = -j Z_o \cot \ell/\beta$$

$$Z_i = -j Z_o \cot 2\pi\ell/\lambda \qquad (10)$$

where ℓ and λ are in the same units.

Shorted Line. A lossless line of any length, shorted at the far end, will have an input impedance

$$Z_i = j Z_o \tan \ell/\beta$$

$$Z_i = j Z_o \tan 2\pi\ell/\lambda \qquad (11)$$

Similar lines closed at the far end in an impedance Z_T will have an input impedance

$$Z_i = Z_o \frac{Z_T/Z_o + j \tan 2\pi\ell/\lambda}{1 + j Z_T/Z_o \tan 2\pi\ell/\lambda} \qquad (12)$$

Actual computation of the input impedance is laborious, especially if the load impedance has reactance as well as resistance, and under these conditions the transmission line calculator of P. H. Smith is a valuable tool. (7)

Quarter-Wave Lines. A line any odd multiple of quarter-waves long acts as an impedance inverter, that is, the input impedance is the reciprocal of the terminating or load impedance. Thus, if the far end is open circuited the input impedance is virtually zero (short circuited), and if the far end is shorted, the input impedance is extremely high (open circuited). For this reason, quarter-wave lines may be used as traps to eliminate or suppress harmonics, or, when shorted at the far end, as supports for other lines because the open end may be shunted directly across the line to be supported and no loss of power will be incurred.

A quarter-wave line may also be used as an impedance-matching device for connecting two dissimilar impedances, very much as an impedance-matching transformer is employed in low or medium frequencies.

Thus, a line of characteristic impedance $Z_o = \sqrt{Z_i Z_T}$ will match Z_i to Z_T.

Half-Wave Line. A line any number of half waves long acts like a 1:1 transformer regardless of the characteristic impedance of the line. Thus

$$Z_i = Z_T \qquad (13)$$

Bandwidth. In all of the expressions above, it must be remembered that the properties are dependent upon the line length in terms of wavelength and that, because the Q of a good line is high, effects noted above are only true for a narrow band of frequencies situated about the frequency (or wavelength) in question.

As a single example, consider a quarter-wave section of line to act as a matching transformer between Z_s and Z_T, Z_T being $10Z_s$. At the center of the design frequency, the input impedance Z_i with Z_T connected to the far end will equal Z_s. But at a frequency 20 percent higher or lower than the design frequency, $Z_i/Z_s = 1.4$. This gives some measure of the bandwidth.

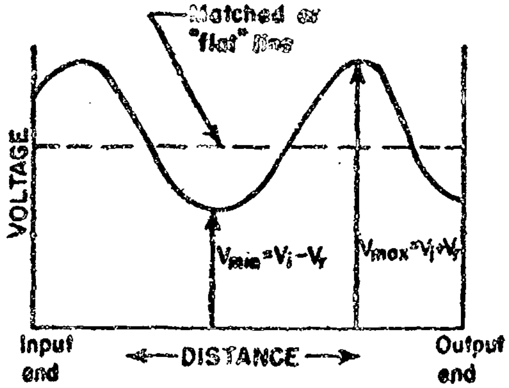
Several quarter-wave sections may be connected in series, the characteristic impedance of each line being properly chosen, and by this technique two impedances may be matched over a much wider band. Coaxial lines, per se, have usable bandwidths of 5 to 6 decades in frequency.

Standing Waves. When a line is terminated in a pure resistance equal to the characteristic impedance of the line, all the power put into the line will be absorbed by the terminating load (minus whatever may be lost in the line itself). If the terminating resistance is some value other than the characteristic impedance of the line, then some power will be reflected back toward the generator from the load end and maximum power will not be transmitted to the load.

The reflected power will set up standing waves on the line because at some distances from the load end the reflected current (or voltage) will be out-of-phase (or in-phase) with the oncoming current (or voltage).

Reflections will occur even if the load impedance is equal to the line impedance because of other impedance changes which occur in the line, because of a sharp bend in the line for example, an imperfect mechanical joint, or because of some reflecting surfaces near an open-wire line.

At any point in the line, a measurement of the relative magnitudes of the incident (Vi) and reflected voltages (Vr) will give a measure of the impedance mismatch between the line and its load or by any device in the system. This ratio is commonly called the Voltage Standing Wave Ratio (VSWR). For a perfect match the VSWR is unity, and for any mismatch this value is greater than unity. (See Fig. 8-1.)



$$VSWR = \frac{V_{max}}{V_{min}} = \frac{V_i+V_r}{V_i-V_r} = \frac{1+\Gamma}{1-\Gamma}$$

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_l-Z_o}{Z_l+Z_o} = \frac{VSWR-1}{VSWR+1}$$

Fig. 8-1. Relationships between line voltages, reflection coefficient (Γ), and VSWR.

Not only is the VSWR important from the standpoint of power transmission, but it is a useful parameter of the system as a whole as it will give evidence of possible line failure. A high VSWR indicates that high currents and voltages will appear at points along the line and may cause excessive heating, due to the current, or dielectric breakdown because of high voltage.

Line Efficiency

Some attenuation of the input power will occur as it progresses down the line, no matter how good a practical line may be. Some power is lost; not all arrives at the load. Thus a 600-ohm open-wire line will have an attenuation of about 0.1 db per 100 feet at 30 Mc; RG-59/U will have about 2 db per 100 feet at the same frequency. These losses in power will result even if the line is properly terminated.

If the line is not properly terminated, that is, if standing waves are present on the line, there will be additional losses of power, the magnitude depending upon the extent of mismatch. Thus the VSWR is a useful parameter in determining the efficiency of the line and load as a whole. If the line attenuation, when matched to the load, is low, indicating that the line by itself is efficient, the additional losses due to mismatch will not be great. As a matter of interest, if the loss is 1 db under matched conditions, the additional loss, if the VSWR is 5, will be approximately 1 db.

Dimensions and Impedance

For two-wire lines in which the spacing D between conductors is large compared to the conductor diameter d

$$Z_o = \frac{276}{\sqrt{\epsilon}} \log_{10} (2D/d) \qquad (14)$$

and for coaxial lines

$$Z_o = \frac{138}{\sqrt{\epsilon}} \log_{10} (D/d) \qquad (15)$$

where

D = inner diameter of the outer conductor

d = outer diameter of the inner conductor

ϵ = relative permittivity.

Two-wire lines have impedances in the general range of 50 to 1000 ohms, may have air, or a solid but flexible material, between the conductors; coaxial lines have impedances in the general region of 20 to 100 ohms and, again, the conductors may be separated by a solid dielectric (usually polyethylene) or by air and small insulating spacers called beads.

The relative dimensions of the conductors of a coaxial line may be chosen to obtain minimum attenuation, maximum power capacity, or the maximum voltage rating for either a fixed outer diameter or fixed mean diameter. For each ratio of conductor diameters, the dielectric constant of the insulation will determine the impedance as shown in Table 8-3 and Fig. 8-2. The impedance is inversely proportional to the half power of the permittivity. Moderate departures from these optimum impedance values do not introduce rapid changes in these electrical characteristics. In the interest of simplicity and standardization of associated devices,

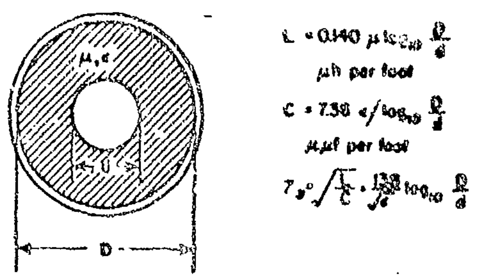


Fig. 8-2. Coaxial line dimensions and constants.

Table 8-3—Comparison of Optimum Diameter Ratios and Impedances for Coaxial Lines

Conditions	Fixed outer diameter (D)			Fixed mean diameter $\left(\frac{D+d}{2}\right)$		
	D/d	Z_o for $\epsilon = 1.0$	Z_o for $\epsilon = 2.26$	D/d	Z_o for $\epsilon = 1.0$	Z_o for $\epsilon = 2.26$
Minimum attenuation (both conductors with the same resistivities)	3.59	76.6	51.6	4.68	92.5	61.5
Maximum voltage (minimum voltage gradient at the center conductor)	3.72	60.0	39.9	3.59	76.5	51.0
Maximum power (fixed power dissipation per unit area of center conductor)	1.65	30.0	19.9	2.09	44.3	29.5

three impedance levels have been established as a reasonable compromise among the many possible impedances:

- **50 ± 2 ohms** Preferred for all microwave applications; test equipment; and transitions to waveguide
- **75 ± 3 ohms** For video, and low r-f use (below 30 Mc); data transmission; very long runs
- **95 ± 5 ohms** Balanced or dual cables, low capacitance, special uses.

Generally, the uniformity or constancy of impedance has a greater effect on circuit performance than the absolute value of the impedance level chosen. The larger, more robust center conductor of a 50-ohm line results in a more stable mechanical structure and a more uniform line. Likewise, the design of connectors with good impedance match is facilitated for 50-ohm lines.

Coaxial Line Attenuation

The attenuation is the real part of the propagation constant. That is,

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} = \frac{R}{2Z_o} + \frac{GZ_o}{2}$$

The r-f resistance (R) of the inner and outer conductor of coaxial lines is well documented in the literature for solid cylindrical shapes and for composite copper and steel conductors. (8,9) For solid copper conductors, this resistance in ohms per 100 feet is

$$R = 0.10\left(\frac{1}{d} + \frac{1}{D}\right) f_{Mc} \qquad (16)$$

For other materials, the resistance of each conductor is directly proportional to the relative conductivity of the material used to that of copper.

To correct for the effects of proximity, spiralling, and contact resistance, a multiplying factor K_1 must be introduced in the first term when a stranded center conductor is used. For a braided outer conductor a similar, but larger, factor K_2 (varying between 2 and 5) must be applied to the second term to account for the complex current paths and their variation with frequency. It is necessary to combine considerable experience with experimental data to estimate the magnitude of these factors accurately for purposes of design. However, the data amassed on very many cable constructions show that, in most cases, their total effect is to increase the overall attenuation by less than 10 percent above the theoretical value except at the frequency extremes. Other effects of braid design will be discussed in greater detail with respect to flexible cables.

The conductor attenuation in decibels per 100 feet can then be expressed as:

$$\alpha_c = \frac{0.435}{Z_o} = \left(\frac{K_1}{d} + \frac{K_2}{D}\right)\sqrt{f_{Mc}} \qquad (17)$$

The center conductor diameter represents the dominating term in Eq. (17) and tends to offset an apparent reduction in losses by increasing Z_o. It will be recalled from Table 8-3, the optimum ratio of D/d for minimum attenuation is 3.59. For rigid lines which have virtually no dielectric losses, or in solid dielectric cables at frequencies below 100 Mc, Eq. (17) is a good approximation of the total losses.

The attenuation due to the dielectric is dependent on the shunt conductance (G) and the geometry of the line:

$$\alpha_2 = \frac{GZ_o}{2} \text{ nepers per meter}^9 \qquad (18)$$

The conductance or "leakage" is due to a vectorial combination of a true d-c conductivity and a quadrature hysteresis loss due to high-frequency molecular polarization. This ratio can be expressed conveniently in terms of the dissipation factor ($\tan \delta$) and the permittivity (ϵ) resulting in (10)

$$\alpha_2 = 2.78 \sqrt{\epsilon} \tan \delta f_{Mc} \qquad (19)$$

It is noteworthy that the dielectric attenuation is independent of the size of the line or its impedance. For most high-frequency dielectrics both $\tan \delta$ and ϵ are almost constant, resulting in a dielectric loss almost linear with frequency. In a solid dielectric cable, these losses become equal to conductor losses in the vicinity of 1000 Mc and predominate beyond that point.

Voltage Rating

The safe voltage that can be applied to a coaxial transmission line is limited by the onset of corona; that is, the ionization of air spaces in the immediate vicinity of a highly localized voltage stress. The intrinsic surge strength of the dielectric materials used for supports is extremely high in comparison with gases. Values for polyethylene are 4000 to 5000 kv per inch on a single pulse and 3500 kv per inch for repeated pulses. (11) The accepted breakdown value for air at standard room pressure and temperature is 76.2 kv per inch or 76.2 volts per mil (30 kv per cm). This value is independent of frequency up to the Mc region and is usually halved for design purposes. Other factors which affect gaseous discharges will be discussed in subsequent sections.

For perfect cylindrical conductors in air, the maximum voltage stress (e_{max}) occurs directly at the face of the inner conductor and is given by:

$$e_{max} = \frac{0.868}{d \log D/d} \text{ or}$$

$$\frac{119.5}{d} \text{ kv/inch or volts/mil} \qquad (20)$$

(The value of Z_o which results in a minimum voltage gradient appears in Table 8-3.)

[9] To convert nepers to decibels, multiply nepers by 8.686.

The maximum peak voltage (V_p') which exists at any point on the line will generally differ from the input voltage when the line is not properly terminated. Its exact value will depend on the degree of mismatch, the electrical length, and the attenuation of the line. However, the ratio of the maximum voltage to the input voltage cannot exceed the actual value of the VSWR which should be used as a conservative derating factor. Further, if the input voltage is amplitude modulated by a factor m, the peak voltage will be increased by a factor of (1 + m). For pulse modulation, the peak voltage is indicated by the pulse description or can be computed directly.

Corona

The voltage at which corona is initiated in an air dielectric line is determined by local stress concentrations such as those caused by a metallic burr on the conductor, the introduction of a sharp corner at a connector, or any marked surface irregularities on the bead. In solid dielectric cables, minute air voids are present within the dielectric and in the neighborhood of the conductors. Recent experiences have shown the interstices around the braid to be the predominating factor for corona initiation, with voids around the center conductor, and bubbles in the dielectric, in that order. (12) Electrical discharges occur within these gaseous voids when the peak voltage exceeds a critical value. This critical value, or corona level, does not vary significantly in a gas from power frequencies to several hundred megacycles. These electrical discharges cause energy losses in addition to normal attenuation, and will eventually lead to complete molecular breakdown of the insulating materials. It is generally necessary to resort to a direct measurement of the corona initiation or extinction levels at power frequencies to establish a practical voltage rating.

Power Rating

The maximum r-f power a coaxial line may safely transmit can be limited either by (1) the voltage introduced due to the peak power or (2) the thermal heating due to the average power. Which of these is the predominating factor will vary according to operating conditions and the design of the transmission line. The peak power (P_v) rating is determined directly by the voltage rating, and expressed by

$$P_v = \frac{V_p^2}{2Z_o} \qquad (21)$$

The peak power is affected by any of the design features, mechanical imperfections, or external factors which tend to degrade the corona level. (13,14,15) For CW, dielectric losses may limit the power to a value below that of Eq. (21) because of heating.

The average power handling capacity will be determined by the attenuation in the line, and the maximum "hot spot" temperature that the dielectric or conductor can withstand continuously. Excessive temperature can result in conductor migration due to softening of the dielectric, mechanical damage due to differential expansion, or shortened life due to chemical deterioration. The amount of heat generated (W) in a matched system is the difference between the input power (P_1) and the output power (P_2) in watts per unit length of line. The ratio of these two powers is a function of the attenuation per unit length (generally per foot). These relationships can be combined to yield Eq. (22).

$$\alpha_{(db)} = 10 \log_{10} (P_1/P_2)$$
$$W = P_1 - P_2 = P_1 \left[1 - \frac{1}{\operatorname{antilog}_{10} (\alpha/10)}\right] \tag{22}$$

The rate of heat dissipation from the line depends on the diameter, materials, and color of the outer covering, and the ambient temperature and altitude. The amount of heat which flows radially from the line will depend on the composite thermal resistivities (R_{th}) of the dielectric and any jacketing materials used, and the temperature gradients present therein. Heat is generated internally at the center conductor, within the dielectric, and at the outer conductor in direct proportion to their individual attenuation. By equating the heat generated, Eq. (22), to the heat dissipated for a given temperature rise (ΔT) between the center conductor and the ambient temperature, Eq. (23) can be established.

$$W = \frac{\Delta T}{R_{th}} = P_t \left[1 - \frac{1}{\operatorname{antilog}_{10} (\alpha/10)}\right]$$

$$\text{or} \qquad P_t = \frac{\Delta T}{R_{th} \left[1 - \frac{1}{\operatorname{antilog}_{10} (\alpha/10)}\right]} \tag{23}$$

where P_t = maximum average power rating. Thus, for any particular physical construction, the average power rating will depend on the permissible temperature rise above a stated ambient. Direct computation of power handling capacity has been made although empirical techniques are generally preferred. (16)

Longitudinal variations in voltage and current as a result of a mismatched load will reduce the average permissible power. When attenuation is small so the VSWR is nearly constant over the entire length, then:

$$\frac{\text{Average power lost in the line with VSWR}}{\text{Average power lost in the line (matched)}} \approx 1/2 \left[\text{VSWR} + \frac{1}{\text{VSWR}}\right] \tag{24}$$

Axial heat flow, particularly in the center conductor, tends to reduce its temperature for short wavelengths. (14) When the wavelength is very long, the power rating for the matched line should be divided directly by the VSWR. The maximum temperature rise occurs at the point of the VSWR minimum.

The amounts by which the power handling ability of Teflon and polyethylene cables decreases with VSWR, altitude, and temperature are shown in Fig. 8-3. (17, 18)

Frequency Range

The upper frequency limit of a coaxial structure is determined by the frequency at which higher order waveguide modes will be propagated. This occurs when the mean diameter becomes equal to one wavelength in the dielectric media (TE_{11} mode). Practical experience dictates that coaxial lines should not be used at frequencies beyond 0.95 of the cutoff frequency (f_c) except in special applications. Beyond this point, there is an extremely sharp rise in attenuation due to energy conversion to this spurious mode. Equation (25) gives this value to within 3 percent.

$$f_c\ (\text{Mc}) = \frac{7520}{(d + D)\sqrt{\epsilon}} \tag{25}$$

For bead supported lines, frequency limitations may occur as a result of bead spacing or bead thickness, which cause resonances at certain critical frequencies. For example, the maximum VSWR of a single uncompensated bead occurs when the bead thickness is equal to a quarter wavelength. Then the VSWR is numerically equal to ϵ in value. Schemes have also been devised for the spacing of such beads so as to limit the VSWR which can occur due to cumulative reflections from each of the bead faces. (15) However, all lines currently used for microwave frequencies provide im-

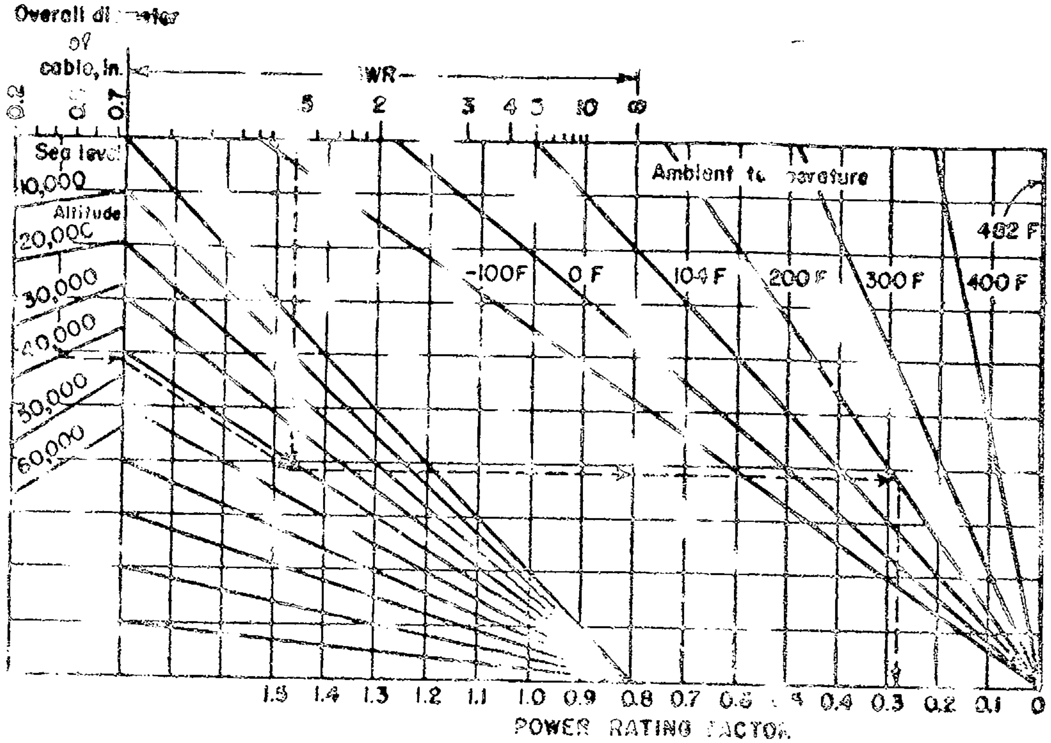


Fig. 8-3. (A) Power derating factors for Teflon transmission lines as a function of VSWR, altitude, ambient temperature, and Cable diameter.

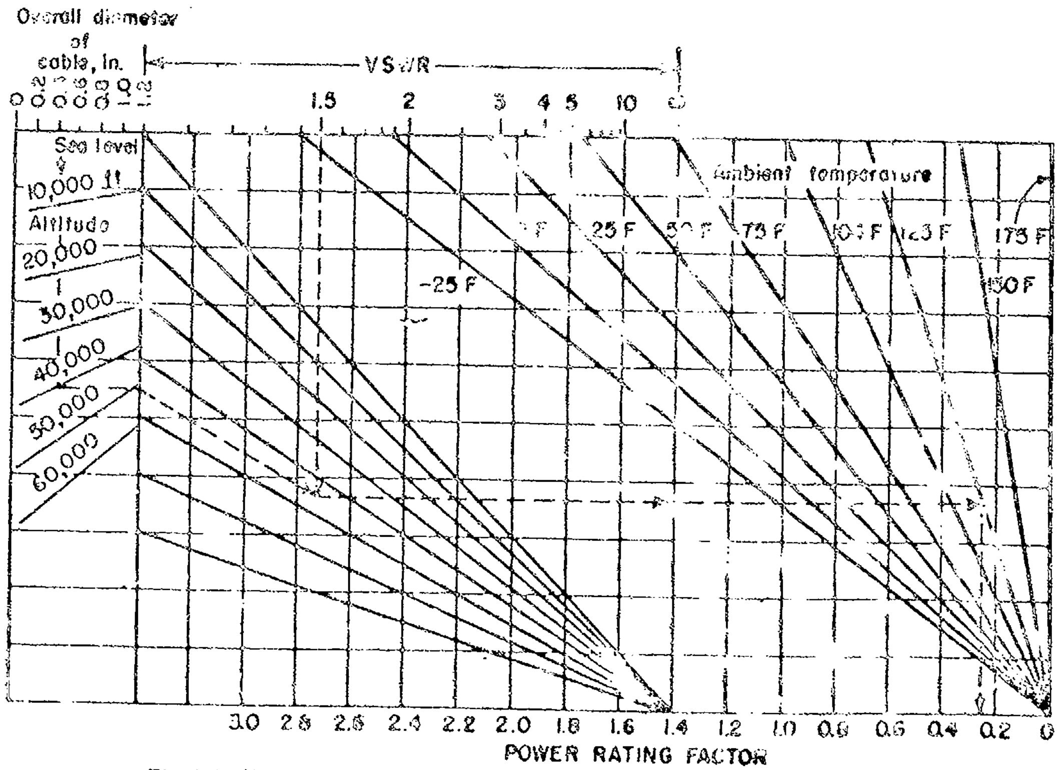


Fig. 8-3. (B) Power derating factors for polyethylene transmission lines as a function of VSWR, altitude, ambient temperature, and cable diameter.

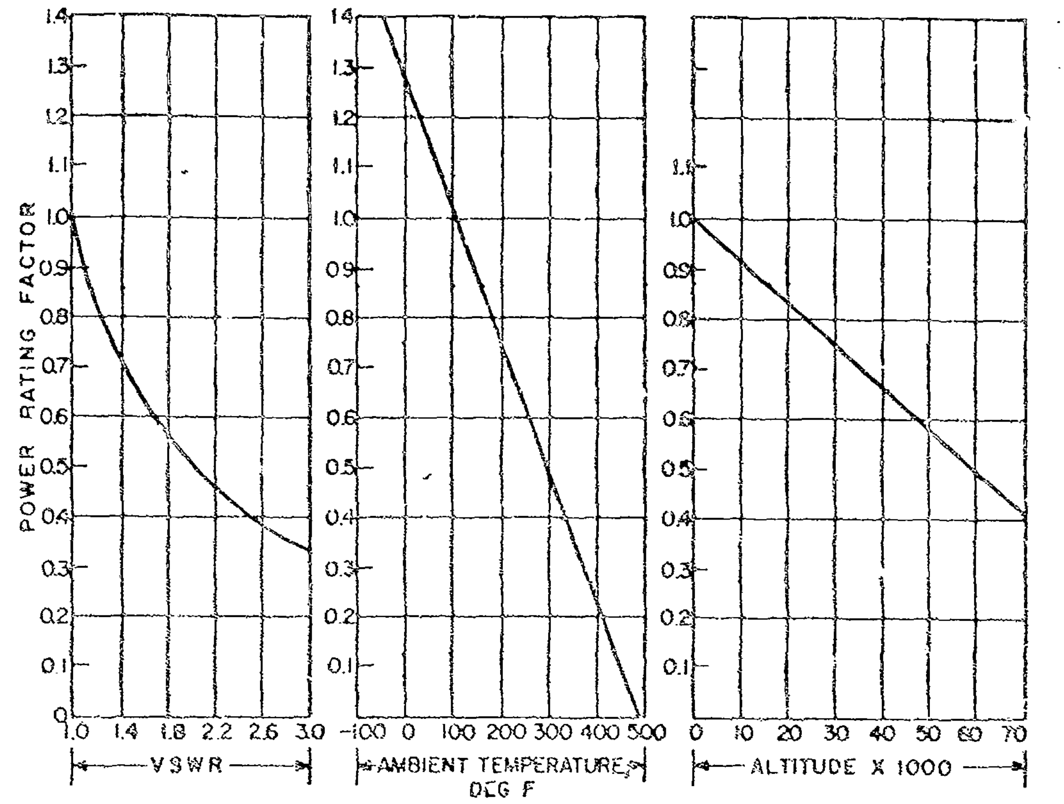


Fig. 8-5. (C) Composite chart for Teflon cables.

pedance matching for the support structure to render them "electrically transparent."

Shielding

Interference or crosstalk can occur between a coaxial line and the surrounding media as the result of radial propagation of energy through the outer conductor. (18) This energy is diminished by (1) attenuation due to penetration into the material of the shield and by (2) reflection of the wave due to impedance discontinuities at the interfaces of the materials employed in the shield structure. The former varies directly as the wall thickness, and as the half power of the frequency, conductivity, and relative permeability of the material. It applies to a tightly woven braid at frequencies below approximately 50 Mc. Above this frequency, leakage occurs due to the finite openings present at the braid crossovers. This coupling loss appears as a small series inductance whose value is virtually independent of frequency. (18)

The reflection loss at each change of shielding material is frequently greater than the loss due to attenuation through the material. The intrinsic impedance (η) of any media is equal to:

$$\eta = \frac{j\omega\mu}{G + j\omega\epsilon} \qquad (26)$$

The higher the ratio of the intrinsic impedances between media, the greater the reflections and the more effective the shielding. For example, the impedance ratio of copper and steel is about 50 and their use as a double braid forms a very effective low-frequency shield. Greater shielding can be achieved in flexible cables by alternately interleaving layers of high-impedance (dielectric) and low-impedance (conductor) materials. Some of these special constructions will be discussed in connection with pulse cables.

The "surface transfer impedance" is the most practical unit of measuring the effectiveness of shielding. It is defined as the ratio of the longitudinal electric intensity on the surface of the outer conductor, to the total current carried by the inner conductor. (19) It is a function only of frequency and the design parameters of the line.

RIGID COAXIAL LINES

Rigid lines of low attenuation and excellent power handling capacity have long been the mainstay of commercial broadcasting, and were used in the low-frequency radars early in World War II. Now they have extensive use in uhf and vhf television and communication where, for moderate powers, they are much more compact than waveguides.

Construction

The conductors for rigid lines are fabricated from precision tubing of high-conductivity hard-drawn copper or brass for the outer conductor. Extruded aluminum and copper-coated stainless steel have also been used to a limited extent. The center conductor is rigidly supported by some type of dielectric bead or pin, mechanically crimped or press-fitted between the conductors. Rigid lines are designated by the nominal overall diameter of the outer conductor and are supplied in 20-foot sections with couplings at each end.

Brief mention should also be made of the 50-ohm stub-supported microwave lines used in World War II military equipments. Their inner conductor is positioned by a series of short-circuited quarter-wavelength coaxial stubs placed at convenient intervals. The stubs present a very high impedance in shunt with the line over the very narrow band of frequencies for which they are effectively a quarter wavelength. However, they are cumbersome to install, difficult to manufacture, and can be completely replaced by newer broadband bead-supported types.

Dimensions

Issuance of Electronic Industries Association (EIA) Standard TR-134 and Military Specification MIL-L-3890 established a common series of standard dimensions for 50-ohm lines as shown in Table 8-4. These dimensions are predicated on the use of an electrically transparent supporting structure. Earlier bead-supported lines had a nominal 51.5-ohm itera-

Table 8-4 — 50-Ohm Air Dielectric Rigid Coaxial Lines

Type	Line size	Physical characteristics				
		Outer conductor diameter (in.)		Inner conductor diameter (in.)		Approximate weight (lb/ft)
		O. D.	I. D.	O. D.	I. D.	
RG-152/U	6-1/8	6.125 ±0.005	5.981 ±0.008	2.600 ±0.004	2.520 ±0.004	6.63
RG-154/U	3-1/8	3.125 ±0.005	3.027 ±0.005	1.315 ±0.003	1.231 ±0.003	3.63
RG-153/U	1-5/8	1.625 ±0.003	1.527 ±0.003	0.6640 ±0.0025	0.5880 ±0.0025	1.38
RG-155/U	7/8	0.8750 ±0.0025	0.7850 ±0.0025	0.341 ±0.003	0.291 ±0.003	0.94
RG-151/U	3/8	0.375 ±0.003	0.289 ±0.003	0.125 ±0.002	Rod	0.10

Type	Electrical Characteristics											
	Iterative impedance* (ohms)			VSWR†	Transducer loss†		TE_{11} mode cutoff frequency (kMc)					60 cycle test voltage, kv, peak
								Teflon, ϵ = 2.11		Polystyrene, ϵ = 2.56		
	Nominal	Max	Min		db/100 ft	Test freq. (Mc)	Air Line	Under-cut	Over-cut	Under-cut	Over-cut	
RG-152/U	50	50.15	49.82	1.10:1	0.140	500	0.789	0.680	0.472	0.469	0.390	33.0
RG-154/U	50	50.24	49.75	1.10:1	0.450	800	1.580	1.365	0.931	1.234	0.770	19.0
RG-153/U	50	50.53	49.64	1.10:1	1.40	2,000	3.096	2.838	1.947	2.506	1.520	11.0
RG-155/U	50	50.57	49.48	1.10:1	3.90	3,500	6.218	5.223	3.593	4.873	3.265	6.0
RG-151/U	50	50.83	49.07	1.10:1	15.0	10,000	18.000	14.387	9.895	13.423	8.135	2.2

* The iterative impedance for each line size is exclusive of supports.

† Test limits of MIL-L-3890. Tests made on 20-foot lengths, minimum.

tive impedance in accordance with EIA Standards TR-103 and TR-104B, "Transmission lines for FM Broadcasting 88 - 108 Mc" and "Television Broadcast Transmitters 44-216 Mc" respectively. Data on these 51.5-ohm lines are also included as Table 8-5 in view of the large number of installations in which they may be found.

Lines in other impedance ranges generally utilize the same size outer conductors as the 50-ohm types. The 75-ohm line is popular as it most nearly approaches the minimum attenuation for given ratios of the conductor diameters as shown in Table 8-3, and its upper frequency limit is approximately 20 percent higher than a 50-ohm line with the same overall diameter. For example, a 6 1/8-inch 75-ohm line will encompass the full uhf television band (478 to 890 Mc). Proposed dimensions for 75-ohm lines have been indicated in Table 8-6 as the future standard.

Center Conductor Support

The method used to support the center conductor will have a marked effect on the iterative impedance as the frequency is increased and will limit the upper frequency that can be covered by the line. At low frequencies, a simple concentric dielectric support or bead will suffice, provided the iterative impedance and propagation constant are corrected for the weighted average permittivity. (20) At microwave frequencies where the bead occupies an appreciable fraction of a wavelength, the conductor diameters must be adjusted at the bead to maintain a constant impedance. Various bead constructions are illustrated in Fig. 8-4. The undercut bead is the most popular due to its simplicity of manufacture. Typical data are shown in Table 8-7 on two such broadband 50-ohm designs. (21)

Special lines have been constructed with impedances in the range from 125 to 180 ohms. They are used for low-frequency applications where it is desired to keep the capacitance as low as possible, or for special matching or tuning purposes. The Navy has made extensive use of a 180-ohm 3 1/8-inch size for matching to shipboard antenna. The greatly reduced diameter of the center conductor severely lowers their operating voltages and causes the capacitance of these lines to be sensitive to temperature variation and mechanical vibration.

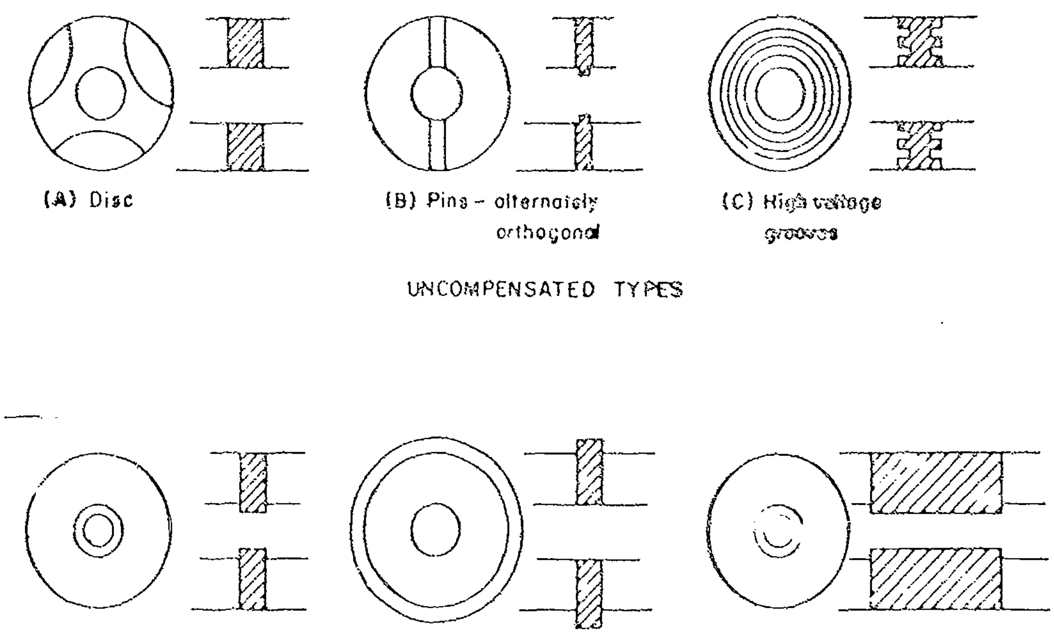
In most transmitting applications, the permissible attenuation, rather than the power capacity, governs the choice of line size. The loss due to the dielectric supports is virtually zero, and the attenuation is readily determined from Eq. (17) and the relative

Table 8-5—Data on 51.5-Ohm Rigid Lines (TR-104-B)

Line size (in.)	Outer conductor (in.)	Inner cond. min. cond. = 95% (in.)	Insulators steatite K = 6 ±0.5 loss factor = 0.004 max	Z_o without insulators	Requirements at 200 Mc		
					Z_o	db/100 ft	Average power
7/8	OD 0.875 ±0.002 ID 0.785 ±0.002	OD 0.3125 ±0.002 ID 0.2625 ±0.002	Beads 0.1875 in. effective thickness × 8-in. spacing	55.2	51.1 ±1.5	0.678	2.0
1-5/8	OD 1.625 ±0.003 ID 1.572 ±0.002	OD 0.625 ±0.002 ID 0.569 ±0.002	Beads 0.108 in. effective thickness × 12-in. spacing	53.5	50.9 ±1	0.34*	7.0
3-1/8	OD 3.125 ±0.003 ID 3.027 ±0.003	OD 1.200 ±0.002 ID 1.138 ±0.002	Beads 0.375 in. effective thickness × 12-in. spacing	55.8	50.5 ±1	0.220	27.0
6-1/8	OD 6.125 ±0.003 ID 5.981 ±0.003	OD 2.500 ±0.003 ID 2.435 ±0.003	Pin type construction, 12-in. spacing	52.3	51.5 ±1	0.081	118.0

Table 8-6—Proposed Inner Conductors for 75-Ohm Air Dielectric Rigid Coaxial Lines

Line size (in.)	Inner conductor diameter (in.)		Iterative impedance (ohms)			TE_{11} mode cutoff frequency (kMc)				
						Air line	Teflon		Polystyrene	
	O.D.	I.D.	Nominal	Max	Min		Undercut	Overcut	Undercut	Overcut
6-1/8	1.716 ±0.004	1.636 ±0.004	75	75.14	74.70	1.003	0.757	0.431	0.699	0.332
3-1/8	0.869 ±0.003	0.789 ±0.003	75	75.20	74.59	1.982	1.495	0.852	1.381	0.656
1-5/8	0.438 ±0.002	0.362 ±0.002	75	75.27	74.48	3.929	2.964	1.689	2.737	1.301
7/8	0.226 ±0.002	0.178 ±0.002	75	75.53	74.09	7.643	5.763	3.285	5.324	2.531
3/8	0.082 ±0.001	Rod	75	75.74	73.43	21.051	15.881	9.068	14.685	8.970



(A) Disc

(B) Pins – alternately orthogonal

(C) High voltage grooves

UNCOMPENSATED TYPES

(D) Thin undercut

(E) Thin overcut

(F) Half wavelength undercut

COMPENSATED TYPES

Fig. 8-4. Typical bead constructions.

Table 8-7—Broadband 50-Ohm Coaxial Lines

Line size (in.)	AN nomenclature	Signal Corps drawing	Upper frequency limit	Max VSWR of 10-ft section with 3 beads	Max VSWR of connector
7/8	CG-1374/U	SC-DL-33600	4 kMc	1.06 at 1.1 kMc	1.027 at 4 kMc
1-5/8	CG-1373/U	SC-DL-33632	2.5 kMc	1.05 at 1.0 kMc	1.013 at 1.1 kMc

conductivities of the materials. As the center conductor accounts for about 73 percent of the losses, its surface must be kept particularly clean and smooth. Figure 8-5 illustrates curves of attenuation vs. frequency for typical commercial lines in the 50- and 75-ohm region. These include a 10 percent derating factor from the theoretical values to account for contact resistance at connectors, surface oxidation, and other factors encountered in use.

Power Rating

Two criteria have been used to establish the average power ratings of air lines. Standards TR-103 and TR-104B recommend half of the power required to raise the outer conductor temperature 40 C for a horizontal run in still air. This is equivalent to a maximum temperature rise of 23 C on the outer conductor. Standard TR-134 limits the maximum inner conductor temperature to 100 C at an ambient temperature of 50 C. The latter is more conservative based on comparative data by RCA on their 3 1/8-inch lines at 200 Mc:

Line type	TR-104-B rating	TR-134 rating
51.5-ohm steatite insulators	27 kw	
51.5-ohm Teflon insulated line		32 kw
50.0-ohm undercut Teflon line	40 kw	22 kw 31.5 kw*

* Proposed rating with a 70 C temperature rise (120 C hot spot)

Increasing the allowable center conductor temperature to 120 C makes these ratings somewhat comparable, but increases the rate of oxidation and annealing of the copper. However, even fully annealed copper has an adequate mechanical yield strength for most applications. Figure 8-6 illustrates the variation of average power handling capacity with frequency for the same lines for which attenuation characteristics are plotted in Fig. 8-5. These values must be corrected for the VSWR and by a factor (F_1) which depends on the nature of the modulation of the transmitted signals. Derating factors are shown below for many common applications.

Application	Typical upper limit of VSWR	Ratio of average power to rated transmitter power (F_1)	Ratio of peak voltage to carrier voltage (F_2)
AM (Audio)	2	1	2
AM (100% sine wave)	2	1.5	2
FM	1.75	1	1
TV	1.1	1	1
Pulse	2	Duty Cycle*	1

* Duty cycles usually range between 0.001 and 0.01.

Correction should be made for any increase or decrease of temperature rise, Eq. (23), caused by an abnormal ambient temperature. Temperature limitations of soldering and gasketing materials should be examined carefully in any high-power application. See also Fig. 8-3(A) and (B).

The peak power is limited by voltage flashover which usually occurs radially at the interface between the air and the dielectric support. The exact value depends on the relative humidity, the surface roughness of the dielectric, the presence of metallic burrs, and similar factors which are very difficult to estimate. It is customary to use direct measurements at power frequencies to establish safe operating values. Significant improvements in the voltage rating can be obtained by placing concentric grooves in the beads and by avoiding sharp corners in the electric field which will introduce localized corona. A thin film of air ($> 10^{-3}$ cm) at a loose bead will increase the electric field intensity by ϵ and reduce the permissible peak power by ϵ^2. A smaller increase in the electric field occurs in the case of an undercut bead, that is

$$\frac{\epsilon}{\sqrt{\epsilon}-1}$$

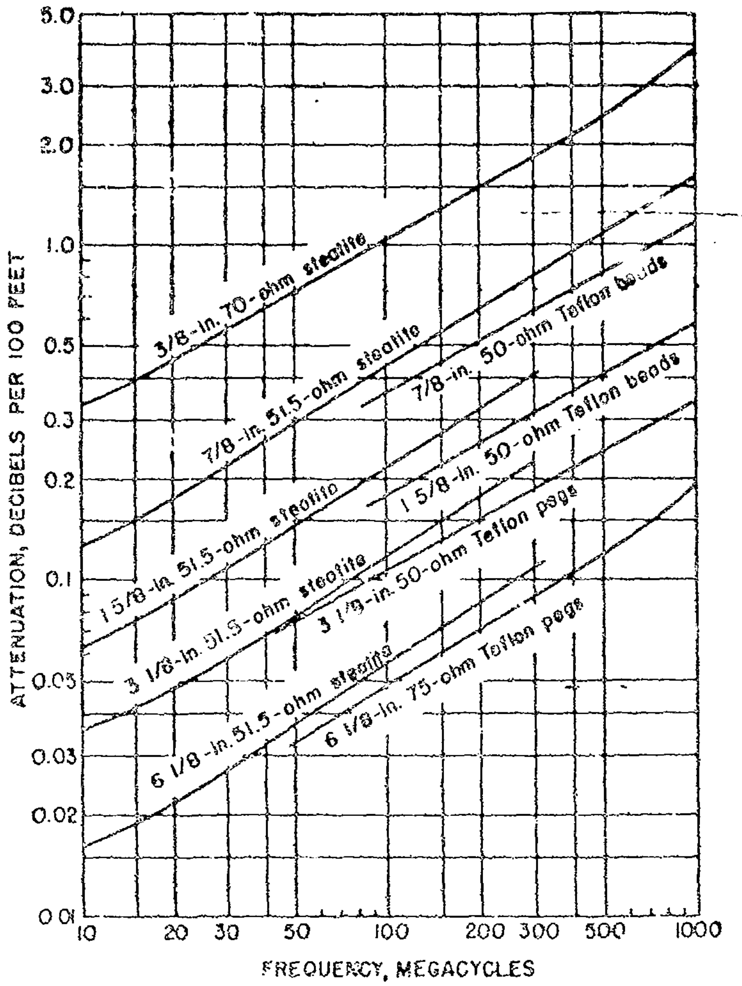


Fig. 8-5. Attenuation vs. frequency, typical rigid coaxial lines.

For r-f operations, the peak value of 60-cycle test voltage, such as indicated in Table 8-4, should be reduced by a safety factor of 2, and by the factor F_2 for amplitude modulation.

Pressurized Lines

It is customary to pressurize rigid lines with a dry inert gas, such as air, nitrogen, or carbon dioxide for more reliable operation. Although the latter two gases have a slight advantage in reducing conductor oxidation, air is more readily available and hence used almost exclusively. A gage pressure of 1 to 1-1/2 psi above atmospheric is adequate to prevent the ingress of moisture due to normal temperature fluctuations. For small systems, static pressure may be maintained by a hand pump or gas cylinder, while the large systems use an automatic motor-driven pump. In either case, the gas should pass through a suitable dehydrating agent, such as silica gel. Higher peak powers can be achieved with one or more atmospheres of pressure and the use of electronegative gases.

Special connectors are provided on rigid line sections to align properly the inner and outer conductors, to assure good electrical contact between them, and to render the junction pressure tight. Earlier couplings consisted of a polarized outside flange and a male contact or "bullet" which was soldered to one of the inner conductors. (32) The more recent military coupling designs are shown unassembled in Fig. 8-7 and in cross section of an assembly in Fig. 8-8. They are asexual and incorporate a self-compensated bead at the coupling to support the weight of the center conductor for continuous vertical runs.

Interchangeable flanges for all line sizes are being adopted as standard by EIA and the military services. However, the contacts shown for the 7/8- and 1 5/8-inch lines are compensated for higher frequency use, and require less cutback of the center conductor than the EIA types. A swivel flange is also available to provide for angular misalignment problems, particularly in right-angle fittings. A large variety of matched fittings can be obtained in each line size to provide angle bends, termination of the line, and gas connections, and to provide interconnection between other line sizes, flexible cable, and waveguide.

Expansion and contraction of the line due to temperature variations may be expected to be about 1-1/2 inches per 100 feet from -25 to +1?5 F. In horizontal runs, full provision must be made for this by the use of swinging hangers or roller supports. For vertical runs on a steel tower, the differential expansion is reduced to about 1/2 inch per 100 feet and can be accommodated by spring hangers. A rigid hanger and two 90-degree elbows are recommended to anchor the line at the antenna and to facilitate its independent test.

SEMIFLEXIBLE LINES

There are many constructional variations between the rigid coaxial lines and flexible cables which fall in the broad category of semiflexible lines. These lines can be fabricated and shipped in continuous lengths from 200 to 2000 feet, which can be formed into moderate be[illegible] during installation. The outer conductor i[illegible] ooth-drawn or corrugated tubing of a ductile metal. Additional protective

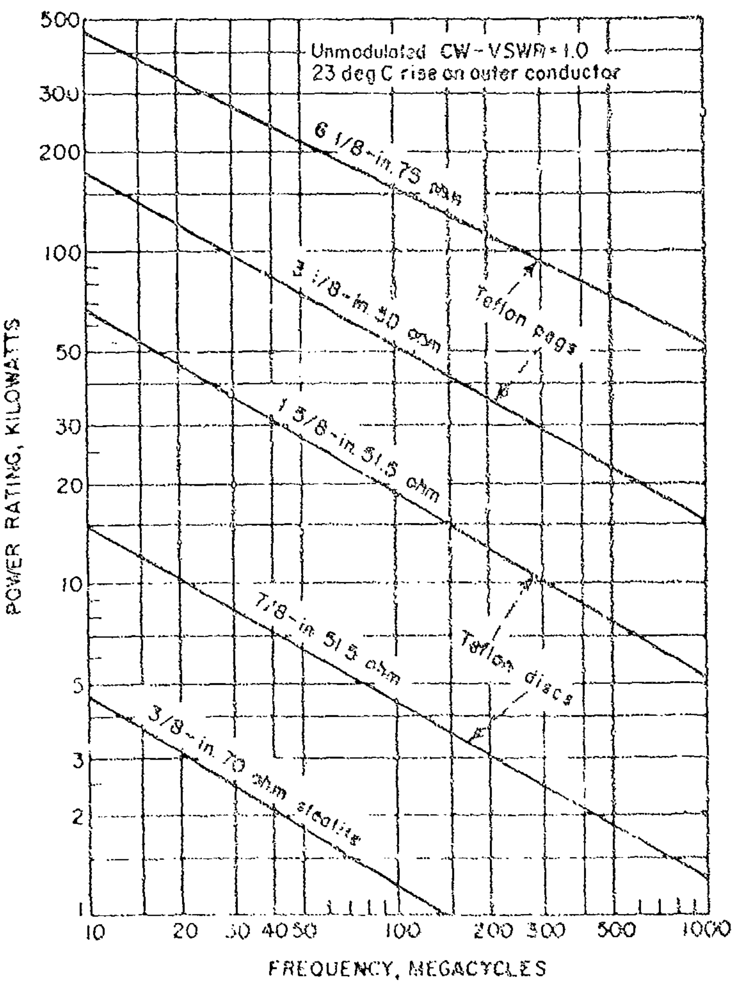


Fig. 8-8. Average power ratings, rigid coaxial lines.

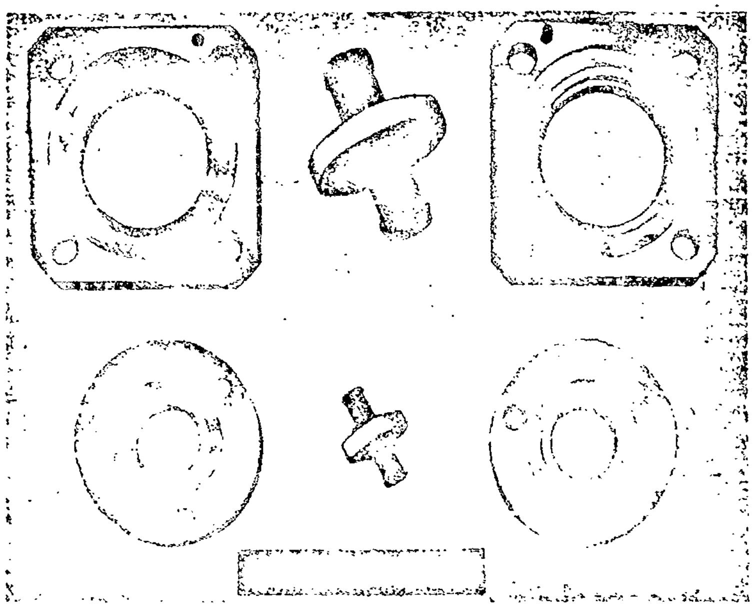


Fig. 8-7. Disassembled couplings for standard 7/8-inch and 1-5/8-inch O.D. coaxial lines.

coverings may be added for greater abrasion and corrosion resistance.

Airspaced Lines

The dielectric of a semiflexible line may be either an airspaced structure or a continuous form of solid insulation. In the former, a continuous ribbon or rod of dielectric material is spiralled openly with a uniform pitch around the center conductor to support it and to maintain a low effective permittivity. Styroflex* cables are manufactured with a continuous laminated helix composed of thin flexible oriented polystyrene tapes. (See Fig. 8-9.) The high tensile and compressive strengths of the Styroflex film (10,000 to 13,000 psi) and the wrapping technique permits the finished cable to withstand high tensile forces and crushing loads. Overall dimensions range from 3/8 to 6-1/8 inches and closely follow rigid line practice. Table 8-6 summarizes the electrical and mechanical data for the 50-ohm types. (23) Comparable designs are also available with impedances of 70 and 77 ohms from 1/2- to 3-1/8-inch diameter. All cables are made with an optional black polyethylene sheath or with special armoring for subterranean or submarine use. In the smaller sizes (3/8 and 1/2 inch) adequate mechanical strength is obtained with an extruded round polyethylene or Teflon filament (Spirafil), which is much simpler and less costly to produce.

The Helical Membrane cable uses a thin flat ribbon of either polyethylene or Teflon to support the inner conductor. This membrane is obtained by cutting a spiral in a hollow dielectric tube of precise size, and an aluminum sheath is drawn down tightly over the open spiral. This construction results in a slightly lower permittivity, attenuation, and cost than the Styroflex, but is not as rugged. It is feasible over the size range from 0.475 to 3.125 inches. Greater care must be taken in the installation to assure that slippage of

* The following trade names are used as a convenient identification of a specific cable construction. The discussion is not restricted to one product, but is intended to encompass all cables of a similar construction:

Styroflex, Spirafil, Foamflex — Phelps Dodge Copper Products, New York, N. Y.

Heliax — Andrew Corp., Chicago, Ill.

Aljak — Amphenol Electronics, Chicago, Ill.

Helical Membrane — The Telegraph Construction & Maintenance Co. Ltd., Greenwich, London, England.
Canada Wire & Cable Co., Toronto, Canada

Pyrotenax — Pyrotenax Ltd., Hebburn, County Durham, England
General Cable Corp., New York, N. Y.

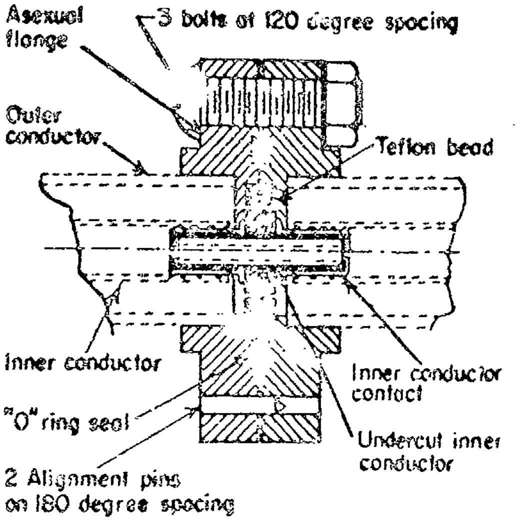


Fig. 8-8. Broadband coaxial line coupler.

the center conductor does not occur due to bends, thermal expansion, or a combination thereof. (24)

The Heliax cable uses a thicker ribbon of polyethylene to support the inner conductor, within a corrugated steel tubing. (25) This tubing is copper clad on the inside for improved conductivity and is protected externally by a bituminous weather-proofing compound, impregnated paper tapes, and a tough vinyl jacket. Heliax cables are presently available in nominal 7/8- and 1-5/8-inch diameters, with consideration being given to the 3-1/8-inch size. No straightening or bending tools are required for field installation. The ability of the outer conductor to withstand repeated flexure (50 to 200 times) about a radius ten times its overall diameter permits reasonable reuse of the cable.

The electrical properties of these airspaced cables are very similar to rigid lines below 100 Mc. In this region, the aluminum outer conductor increases the attenuation about 6 percent. Above 100 Mc, this difference gradually increases with frequency to an ultimate value of 35 to 45 percent above the equivalent size rigid line at cutoff. The impedance variation with frequency is also slightly larger, but still below a VSWR of 1.08 as a result of minor irregularities in the dielectric structure and dimensions of the outer conductor. However, close to the upper frequency limit, a marked lowering of the impedance has been observed due to an increased concentration of the electric field in the dielectric. (26) These cables should be installed with sealed fittings and maintained with a positive dry gas pressure. Fittings are available that are compatible with both rigid lines and flexible cables.

Solid Dielectric Lines

The second category of semiflexible cable uses a solid or continuous form of dielectric in the size range from 0.080 to 0.750 inch. One of the early types (RG-81 and 82/U) uses a highly purified, compacted magnesium oxide insulation, with soft copper conductors. (27) The attenuation of these Pyrotenax cables is somewhat high, particularly at the higher frequencies, and the insulation is very hydroscopic when exposed to the atmosphere. More recent designs use polyethylene or Teflon (Aljak) or foamed polyethylene (Foamflex) with an alumi[illegible] sheath. The introduction of a solid dielectric increases the peak operating

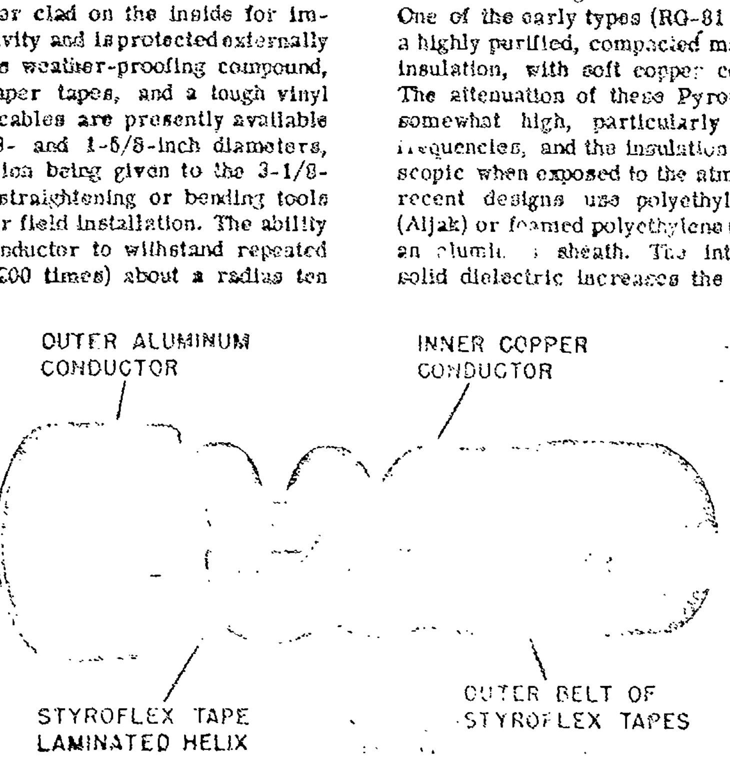


Fig. 8-9. Cutaway section of Styroflex cable.

Table 8-8—Nominal Characteristics of Styroflex 50-Ohm Coaxial Cables

Overall diameter (in.)	Dielectric constant	Capacitance (mmf/ft)	60-cycle peak test voltage (kv)	Inner conductor (in.)		Outer conductor (in.)		Minimum installed bending radius (in.)
				Wall	O.D.	I.D.	O.D.	
3/8	1.40	24	2.2	Solid	0.112	0.298	0.375	4
1/2	1.34	24	3.4	Solid	0.132	0.421	0.500	5
3/4	1.26	23	5.0	Solid	0.251	0.632	0.750	7.5
7/8	1.23	22	6.0	Solid	0.300	0.758	0.875	10
1-1/8	1.23	22	8.0	0.051	0.400	1.007	1.125	17
1-5/8	1.20	22	11.0	0.055	0.591	1.472	1.625	25
3-1/8	1.18	22	19.0	0.071	1.157	2.850	3.125	50
6-1/8	1.16	22	45.0	0.118	2.25	5.512	6.125	90

voltage and the attenuation, but lowers the thermal resistance sufficiently to retain the equivalent power handling capacity of an air-spaced line. Semiflexible lines without a jacket have a smaller volume and improved power rating in comparison to flexible cables of the same diameter over the dielectric. The solid outer conductor also has a lower attenuation than a braided cable. The solid dielectric semiflexible cables can be permanently sealed for high altitude or for submarine use without the need for auxiliary pressuring equipment. Although an exact comparison is not possible due to dimensional difference, Table 8-9 illustrates the gradual transition of characteristics on various 50-ohm types in the 3/8-inch nominal size ranges.

Semiflexible cables provide a compact, rugged installation, with the mechanical protection equivalent to lightweight conduit for permanent interconnection within open cable raceways, along bulkheads, and in similar situations. Intimate contact with any metallic supporting structure enhances their internal heat dissipative properties. Aluminum is finding increasing use due to its lighter weight, lower cost and nonstrategic nature in comparison with copper. The proper tools must be used to avoid any sharp bends or kinks in

Table 8-9—Comparison of Various 50-Ohm Semiflexible Cables

Commercial type →		Helical membrane	Styroflex	Foamflex	Aljak	Aljak	Pyrotenax	RG-8/U
Dielectric		Air-spaced		Solid dielectric				
		Polyethylene ribbon	Polystyrene tapes	Foamed Polyethylene	Polyethylene	Teflon	Magnesium oxide	Polyethylene
Outer conductor		Aluminum					Copper	Copper braid
Overall diameter (in.)		0.475	0.375	0.375	0.325	0.325	0.375	0.420
Diameter over dielectric (in.)		0.400	0.398	0.373	0.285	0.285	0.321	0.285
Weight (lb/100 ft)		148	101	--	89	103	172	120
Minimum bending radius (in.)		7	4	4	1.8	1.8	4	2.1
Minimum shipping diameter (in.)		28.5	32	32	6.5	6.5	30	8.8
Upper operation temp. (deg C)		85	85	85	85	200	250	85
Capacitance (mmf/ft)		21.1	24.0	25.0	29.5	29.5	36.0	29.8
Attenuation (db/100 ft)	10 Mc	0.23	0.38	0.38	0.33	0.32	0.53	0.63
	100 Mc	0.75	1.2	1.2	1.5	1.4	1.7	2.2
	1000 Mc	2.6	4.2	5.1	7.6	6.0	6.7	9.0
Average power (kw at 40 C ambient)	10 Mc	2.3*	3.7	5.2	3.7	17.0	--	3.1
	100 Mc	0.73*	1.2	1.5	1.0	5.2	--	0.70
	1000 Mc	0.21*	0.34	0.35	0.30	0.50	--	0.20
Operating voltage (kv peak)		1.3	1.1	--	6.0	6.0	4.5	8.0

* Based on a 35 C ambient temperature.

unreeling and installing cable, and with such care, cable can be reused.

Precautions should be taken to prevent continual vibration from "work hardening" and eventually cracking the sheath. Copper sheath is better than aluminum from the standpoint of vibration resistance. These cables can withstand short-time operation in the presence of open flames. Sustained use above their rated temperature will cause damage to the cable sheath due to the relatively large thermal coefficient of expansion of the dielectric. However, mineral-insulated types can be used up to 250 C for limited operation up to about 100 hours, and close to the softening point of copper under emergency conditions.

Unprotected copper or aluminum can be used outdoors in dry locations or in aerial installations where there is no danger of electrolytic action. In wet locations, or in the presence of corrosive vapors, the sheath should be protected with asphalt coated tapes, or a jacket of black polyethylene or vinyl. A metallic armor is recommended for additional mechanical protection when underground or underwater burial is required.

FLEXIBLE CABLES

Flexible cables are the simplest, most versatile, and popular means of transmission of r-f and microwave energy. Since 1942, they have been improved continually with regard to temperature range, attentuation stability, and operating voltage. Their extensive use has also been a major incentive for the development of new high-frequency dielectric materials and new production techniques. Coaxial cables have been made in a wide range of sizes and electrical characteristics. Discussion and data herein are limited to the most used or "standard" coaxial types with dual and twin cables, pulse cables, and special-purpose cables being treated in subsequent sections.

Specifications

Cables are identified universally by their military nomenclature (consisting of the component indicator, RG); a dash followed by an arbitrary serial number with suffix letters designating subsequent design changes; a slant line and the suffix U indicating general utility (for example, RG-8A/U). The component indicator RG applies to all unterminated lengths of r-f transmission lines and waveguides. (28) The majority of cables are procured in accordance with Specification MIL-C-17B, "Cables, Radio Frequency, Dual Coaxial, Twin Conductor and Twin Lead," or by interim drawings or specifications which refer to it. As of August 1957, the Air Force planned to utilize MIL-C-17B for all general purpose cables. In addition, Air Force specifications are of two types, one for special-purpose cables and one for new experimental types to be brought under MIL-C-17B at a later date. A waiver is required for the use of either of the latter two types of cable since single-service specifications are not listed in the coordinated installation specification MIL-W-5088. The EIA Standard 134, "Solid Dielectric Cables," is very similar to MIL-C-17, but is restricted to the more common polyethylene types. Many of these cables are also being adopted for military applications by the North Atlantic Treaty Organization (NATO) countries and, for commercial applications, through the International Electrotechnical Commission.

A brief summary of the contents of several of the military specifications in most general use is given in Table 8-10.

Construction

All cables consist of the same basic elements: a center conductor, a low-loss solid or semisolid dielectric, and one or more braided outer conductors followed by a waterproof covering. Over this covering, medium and large size cables may also have an armor, or a lead sheath, or lead sheath and an armor. Many compromises are involved as to the choice of materials and constructional features of each of these elements to attain good overall electrical and mechanical performance under a wide range of environments. Some of these factors are discussed briefly below.

Center Conductor. Solid copper is used for conductors above approximately 0.100 inch in diameter and concentric stranded conductors (7, 19, or 27 strands) below 0.100 inch for greater flexibility except for certain miniature cables where adequate flexibility can be achieved with a solid conductor. In these small size cables, the majority of the flexing stress is absorbed by the dielectric and jacketing materials whose strength exceeds that of the conductor. Thus, the conductor does not, in general, limit the flex life of the completed cable.

Single copper-clad steel conductors also provide good flexibility and add mechanical

strength in the small and miniature sizes and in the airspaced cables.* Silver coatings are necessary on high-temperature cables to prevent rapid oxidation of the copper during processing and use. Nickel coatings are also used for this purpose. Tin coatings are used to facilitate soldering of cables to fittings.

Tin- and nickel-plated conductors should be limited to low-frequency applications where the thickness of the coating will not increase the conductor attenuation significantly.

Dielectric. Polyethylene is used almost exclusively where the maximum temperature will not exceed 85 C. It is extruded directly over the center conductor in either a solid or airspaced form. Polytetrafluoroethylene (Teflon) is required when temperatures from 85 to 250 C are encountered in the vicinity of the dielectric. It may be extruded and sintered in solid form or built up from layers of tape to achieve greater flexibility. A high-temperature sealing compound must be used to fill the voids in the taped cable, except in the miniature sizes where the tapes can be adequately heat fused.

Outer Conductor. A single close fitting braid of fine copper wire (0.010 to 0.004 inch) is used most frequently. Tin- or silver-coated strands are used for the same reasons as on the center conductor, as well as reducing the apparent r-f resistance of the braid. A second braid of either copper or steel is used to improve shielding. The second braid has only a secondary effect on the attenuation and is designed primarily for improved flexibility and shielding.

Jacket. Black vinyl resins are extruded or tubed over the outer conductor of all polyethylene dielectric cables. Cables with Teflon dielectric have a close wrap of Teflon tape, followed by one or more glass braids impregnated with a silicone varnish. An extruded rubber sleeve with a Dacron braid impregnated with a fluorocarbon lacquered can be used to improve the very poor abrasion resistance of the glass braids. For miniature cables, a wide variety of jacket materials is available with different upper temperature limits, such as extruded Teflon or heat-fused tapes or Teflon-impregnated glass (200 C), extruded monochlorotrifluorethylene (H Kel-F, Flurothene or Polyfluron) (135 to 150 C), extruded nylon over vinyl or heat fused or lacquered nylon braid (105 to 125 C). Consideration is also being given to the use of high molecular weight polyethylene, pigmented black, for polyethylene cable where the temperature will be kept below 85 C.

Protective Coverings. A close braid of aluminum armor and paint is applied over the jacket for shipboard installations. An armor also protects the jacket against cuts and tears in hazardous locations or during burial in rocky terrain. Cables for permanent burial in wet locations have a lead sheath over the jacket for added long-time moisture resistance. A serving of heavy-duty galvanized steel armor wire, embedded in layers of asphalted jute, is necessary for the installation and recovery of these heavy leaded cables.

The mechanical characteristics of these cables are adequate to withstand normal field usage. The present vinyl jackets have a temperature range from -40 to +100 C, are water and weatherproof, flame and solvent resistant, with good abrasion and tear properties. Experimental work indicates that a silicone rubber-lacquered polyester fiber braid jacket has an abrasion resistance nearly as great as vinyl used on polyethylene cable and is useful over the range -55 to 200 C. The Teflon tape and glass braid coverings have a wider temperature range (-55 to 250 C) but are somewhat less rugged, particularly with respect to abrasion resistance. Their behavior will be discussed more fully under "Environmental Factors."

Cables can be grouped most conveniently in terms of their diameter over dielectric

---

* Miniature coaxial cables using seven strands of No. 38 AWG nickel-plated annealed copperweld center conductors are furnished by several manufacturers. The conductor has approximately 8 percent elongation and a minimum of 70,000 psi tensile strength. The overall cable strength before breakage of the center conductor is nearly double that of a hard-drawn copperweld conductor. Use of this type of cable is indicated when:

1. Several miniature coax cables are to be bound together into a multiconductor cable.
2. When long runs are necessary.

The conductors are limited to frequencies below 100 Mc in general.

Not enough experience has been accumulated as of August 1957 to indicate the ultimate value of these experimental cables, especially with regard to the attenuation caused by the nickel plating.

It is worth noting that, where danger of nicking the conductor in stripping is possible, the stranded-center-conductor types are preferred to the solid-conductor types. If nicking occurs with the latter, the probability of a complete break in the conductor is much greater than with the stranded conductor where it is unlikely that all the strands would be broken in flexing.

Table 8-10—Military Specifications Concerned with Transmission Lines

Number and title	Scope
Flexible cables	
MIL-C-17B "Cables, Coaxial and Twin Conductor for Radio Frequency Use."	Basic omnibus coordinated specification. Contains virtually all types of flexible coaxial, pulse, and special purpose r-f cables in common use. Includes a few semi-flexible cables.
MIL-C-4866 (USAF) "Cable, Radio Frequency RG-62B/U"	Performance requirements for one type of low-capacitance r-f cable, RG-62B/U superseded by MIL-C-25875 (USAF).
MIL-C-8721 (USAF) "Cable Radio Frequency, Coaxial Miniature"	Miniature Teflon cables, specification superseded by MIL-C-25509 (USAF). Some of the cables are also being included in MIL-C-17B.
MIL-C-15452 (Ships) "Cable, special purpose, (tow) electrical coaxial lead wrapped, nylon covered."	A special lead-wrapped, nylon-covered, coaxial-electric-tow cable to be used for continuous submerged towing at sea.
MIL-C-25509 (USAF), "Radio Frequency RG-115A/U"	Detail requirements for r-f cable, RG-155A/U—superseded by MIL-C-25875 (USAF)
MIL-C-25875 (USAF) "Cables, Radio Frequency, Coaxial"	Flexible and semiflexible shielded cables, for use as r-f transmission lines in airborne radar and communications systems of the Air Force. NOTE: 1. Supersedes MIL-C-25509 by Spec Sheet 25875/3 (RG-115A/U) 2. Supersedes MIL-C-4866 by Spec Sheet 25875/1 (RG-62B/U) This specification encompasses RG-71B, 178A, 179A, 180A/U and 209/U.
Rigid lines	
MIL-L-3890 "Lines, Radio Frequency Transmission" MIL-C-9360 (USAF) "Cable, Radio Frequency RG-134"	Establishes sizes and requirements for 50-ohm conductors, sizes from 3/8- to 6-1/8-inch O. D. Requirements for a specific low capacitance interlocking Teflon bead-supported semiflexible cable.

(D.O.D.). In each size range, cables are available with impedances of 50 and 75 ohms, with a general purpose or high temperature dielectric, and with special additional coverings required for mechanical protection. Table 8-11 summarizes these various constructional equivalents and subsequent data will refer to the nomenclature of the basic cable only. Table 8-12 indicates the general characteristics of these cables; more detailed information is contained in MIL-C-17B.

Power and Voltage Ratings

As would be expected, the voltage and power ratings increase and the attenuation decreases directly with the diameter over dielectric. For the equivalent D.O.D. and con-

Table 8-11—Summary of Cable Sizes and Constructions

Size designation	Nominal diameter over dielectric (in.)	50-ohm cables[a]		75-ohm cables[a]	
		Polyethylene	Teflon	Polyethylene	Teflon
Subminiature	0.034[†] Plain	--	188, 178‡	--	--
Miniature	0.060[†] Plain Armored	174	189	--	187, 179‡
Small	0.016[†] Plain Armored	55A, 58C	141 142	--	--
	0.146[†] Plain Armored	--	--	59A	134, 140
	0.181 Plain Armored	5B	143	6A	--
Medium	0.285[†] Plain	8A, 9B	87A, 115 165	11A, 13A	144
	Armored	10A, 148	116, 166	12A	
	0.370 Plain Armored	14A 74A	94A, 119 139	--	--
Large	0.620 Plain	117, 118	--	--	--
	0.680[†] Plain Armored	17A, 164, 177 18A	--	164 35A, 84A, 85A	--
	0.910 Plain Armored	19A 20A	--	--	--

[a] Teflon cables are the preferred construction for miniature size coaxial cables because of the difficulty encountered in soldering properly these small cables without damage to the polyethylene dielectric.

† Preferred values for future design.

‡ Cable has KEL-F jacket.

struction there is practically no difference between the attenuation, power ratings, or voltage rating of 50- and 75-ohm cables. Figures 8-10 and 8-11 s the variation of attenuation and power rating vs. frequency for the full range of sizes of 50-ohm polyethylene cables. The attenuation curves should not be extrapolated close to cutoff because of their rapid change of slope. Further, the power curves should not be projected to frequencies lower than 10 Mc for C-W operation, since electric breakdown, rather than thermal limitations, will govern. The average power is rated for a 40 C rise above a 40 C ambient temperature (that is, a maximum "hot-spot" temperature of 80 C on the center conductor).

With the increased use of coaxial cables in missiles where a short cable life only is expected, considerable thought is being given to the relationship between temperature and time until failure. Cables are being used beyond their present ratings; but when they are so abused, long life should not be expected.

Temperature Derating

The power correction factors for other ambient or maximum temperatures are indicated below:

Ambient temperature (deg C)	Max. center conductor temperature (deg C)			
	80	75	70	65
	Correction factor			
40	1.00	0.86	0.72	0.59
50	0.72	0.59	0.46	0.33
60	0.46	0.33	0.22	0.10
70	0.20	0.09	0.00	--

The cable size should be selected so that in extremes of operation the center conductor temperature stays below 80 C. Where continuous flexing is involved, 65 C is a recommended maximum.

For higher ambient temperatures or for increased power ratings Teflon cables must be used. While the Teflon can safely withstand

Table 8-12—Characteristics of Standard R-F Cables

Type RG-	Inner conductor	Dia. of dielectric (in.)	Shielding braid(s)	Overall diameter (in.)	Weight (lb/100 ft)	Maximum operating voltage (rms)
50-ohm polyethylene dielectric						
174/U	7/0.0063 Copperweld[a]	0.060	Tinned copper	0.100	0.80	1,000
122/U	27/0.005 Tinned copper	0.096	Tinned copper	0.160	2.0	1,900
58C/U	19/0.0071 Tinned copper	0.116	Tinned copper	0.195	2.9	1,900
55A/U	0.035 Silvered copper	0.116	Two silvered copper	0.216 (max)	3.2	1,900
5B/U	0.053 Silvered copper	0.185	Two silvered copper	0.332	9.3	3,000
8A/U	7/0.0296 Copper	0.285	Copper	0.405	12.0	5,000
9B/U	7/0.0296 Silvered copper	0.285	Two silvered copper	0.425	15.3	5,000
14A/U	0.106 Copper	0.370	Two copper	0.545	23.6	7,000
17A/U	0.195 Copper	0.680	Copper	0.870	49.1	11,000
19A/U	0.260 Copper	0.910	Copper	1.120	74.3	14,000
75-ohm polyethylene dielectric						
59A/U	0.0230 Copperweld	0.146	Copper	0.242	3.2	2,300
6A/U	0.0285 Copperweld	0.185	Inner—silver-coated copper; Outer—copper	0.332	8.2	2,700
11A/U	7/0.0159 Tinned copper	0.285	Copper	0.405	9.6	5,000
13A/U	7/0.0159 Tinned copper	0.285	Two copper	0.425	12.6	5,000
34A/U	7/0.0249 Copper	0.460	Copper	0.630	23.1	6,500
164/U	0.1045 Copper	0.680	Copper	0.870	--	10,000

Table 8-12—Characteristics of Standard R-F Cables (cont)

Type RG-	Inner* conductor	Dia. of dielectric (in.)	Shielding braid(s)	Overall diameter (in.)	Weight (lb/100 ft)	Maximum operating voltage (rms)
50-ohm Teflon dielectric cables						
196/U	7/0.004 Silvered Copperweld	0.034†	Silvered copper	0.080	--	500
188/U	7/0.0067 Silvered Copperweld	0.060	Silvered copper	0.110	1.25	1,200
141/U	0.0359 Silvered Copperweld	0.116	Silvered copper	0.190	3.0	1,900
142/U	0.0359 Silvered Copperweld	0.116	Two silvered copper	0.206 (max)	4.5	1,900
143/U	0.0570 Silvered Copperweld	0.185	Two silvered copper	0.325	10.2	3,000
115/U	7/0.028 Silvered copper	0.250†	Two silvered copper	0.375	--	5,000
115A/U	7/0.028 Silvered copper	0.255	Two silvered copper	0.415	--	500
87A/U	7/0.0312 Silvered copper	0.285	Two silvered copper	0.430	17.0	5,000
119/U	0.102 Copper	0.332	Two copper	0.465	--	6,000
94A/U	19/0.0254 Silvered copper	0.370†	Two copper	0.470	--	7,000
117	0.190 Copper	0.620	Copper	0.730	45.0	7,000
75-ohm Teflon dielectric cables						
187	7/0.004 Silvered Copperweld	0.060	Silvered copper	0.110	--	750
140	0.025 Silvered Copperweld	0.146	Silvered copper	0.233	4.5	2,300
144	7/0.0179 Silvered Copperweld	0.285	Silvered copper	0.410	12.0	5,000

* Copperweld is a trade name for copper covered steel described in paragraph 3.2.1.2 of MIL-C-17.

† Taped Teflon dielectric (Type F-1).

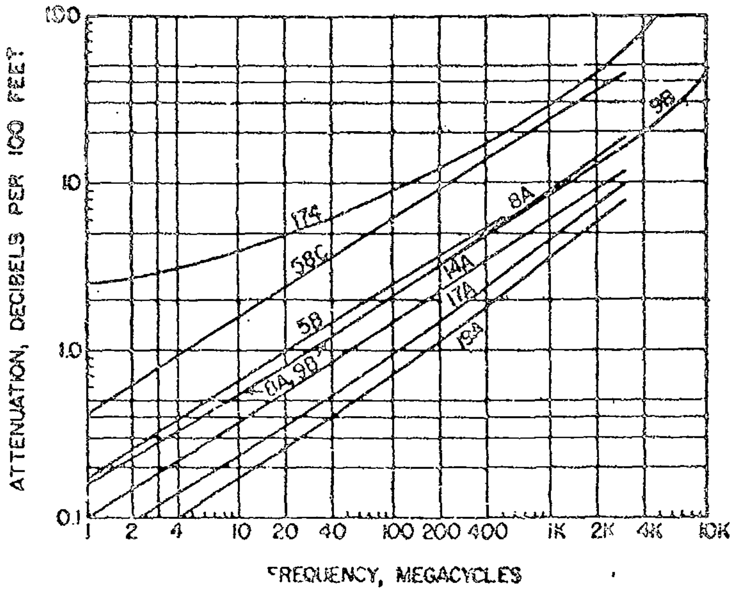


Fig. 8-10. Attenuation characteristics, 50-ohm polyethylene cables.

250 C, its sustained use above 205 C (400 F) is not recommended. Above this temperature, slight traces of gaseous Teflon have been detected, and oxidation of copper becomes quite rapid. A maximum conductor temperature of 205 C is permissible for silver-plated copper but this should be reduced to 150 C for bare copper, particularly if the cable will be subjected to any sustained mechanical loading. Teflon has been used up to 300 C, but the relationship between temperature and life should be clearly understood by the design engineer when such high temperatures are considered. The power ratings plotted in Fig. 8-13 are based on a 250 C maximum conductor temperature for all cables except for the miniature size which is rated at 205 C. (17,29) The 250 C ratings should be reduced by a factor of 0.74 for a maximum temperature of 205 C and by 0.47 for a maximum temperature of 150 C to assure prolonged cable life.

Teflon cables have slightly lower high-frequency attenuation because of the lower dissipation factor and permittivity of the dielectric. Miniature Teflon cables can be installed in cramped quarters with much less hazard of damage from soldering. In the large sizes, they are much stiffer to handle and cannot be procured in as long continuous lengths as polyethylene cables. Their cost is considerably more than their polyethylene counterparts. They should be used only when their superior temperature is mandatory or their improved performance proves economical.

Capacitance

The capacitance of the solid dielectric cables varies inversely with their impedance and averages 21 and 29 1/2 mmf per foot for 75- and 50-ohm cables, respectively. A lower capacitance is often desirable, particularly in high-impedance circuits where the cable shunts the input to the device. To achieve lower capacitances (impedances from 95 to 185 ohms), a very thin center conductor or an airspaced dielectric or a combination of the two is required. Such cables generally employ an open spiral wrap or braid of dielectric to support the center conductor, followed by a concentric tube of dielectric to support the braid and jacket. Data on several popular constructions are shown in Table 8-13.

Attenuation

In the microwave region, the VSWR, looking into a flexible cable, may vary between 1.1 and 1.3 and occasionally reach sharp peaks of 1.6 and 1.8. The magnitude and frequency of occurrence of these sharp resonances increase with cable length and frequency, that is, with the greater number of electrical wavelengths. These resonances are due to additive reflections from changes in characteristic impedance caused by fluctuations in the diameter over the dielectric, ellipticity of

the core, or centering of the conductor. (30) Such small continuous variations are inherent in the nature of the mechanical extrusion process and are more prevalent in Teflon than in polyethylene. For critical applications, individual cables should be measured by frequency-scanning techniques over the specified band of interest.

In addition to reflective losses, a sharp increase in attenuation may occur above 3 kMc due to the braid construction of certain cables. (31) At these frequencies, the intimacy of contact between the individual braid wires has a marked effect on the apparent resistance of the cable. A loose or open braid or any form of surface contamination can cause erratic attenuation when the cable is flexed. The braid structure of the RG-5B/U and 9B/U cables were specifically redesigned to make them stable for microwave use.

CONNECTORS

The coaxial connectors used with cables are usually the limiting factor with respect to VSWR and operating voltage. Connectors are available in various series and sizes within A series to cover the complete range of cables. (The A series comprises all connectors whose mating portions are compatible.) Connectors for the medium size cables such as the C, N, and QDS series are designed primarily for good impedance match in a 50-ohm system. With proper assembly techniques, a mated pair of connectors will exhibit a VSWR of

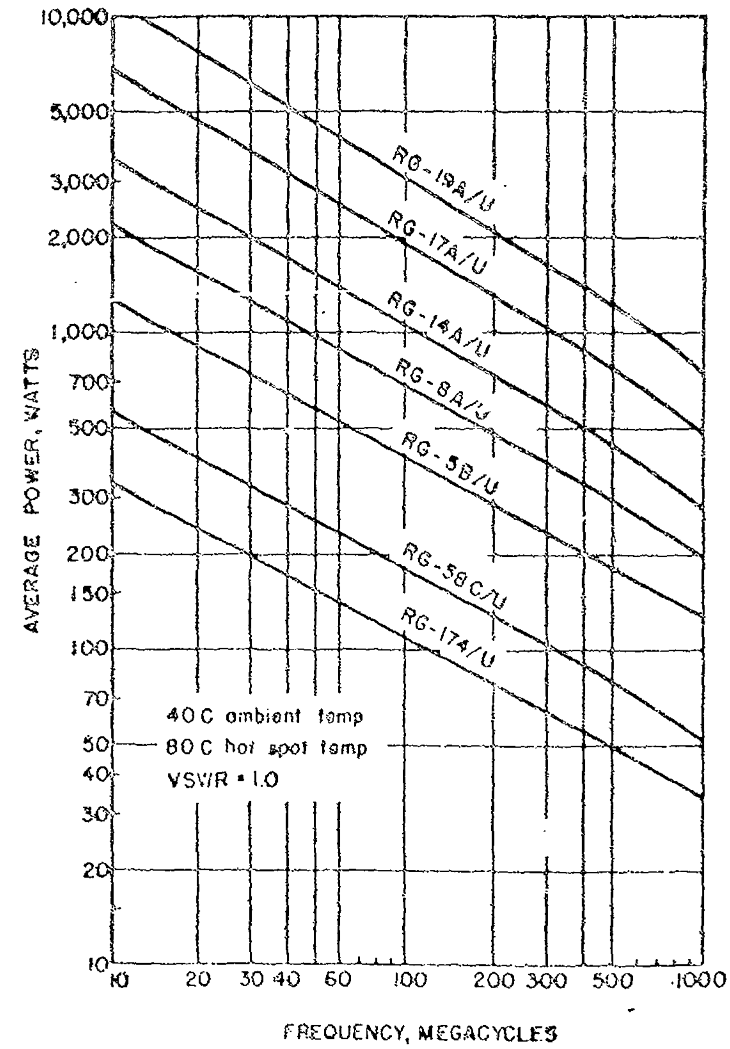


Fig. 8-11. Average power ratings of 50-ohm polyethylene cables.

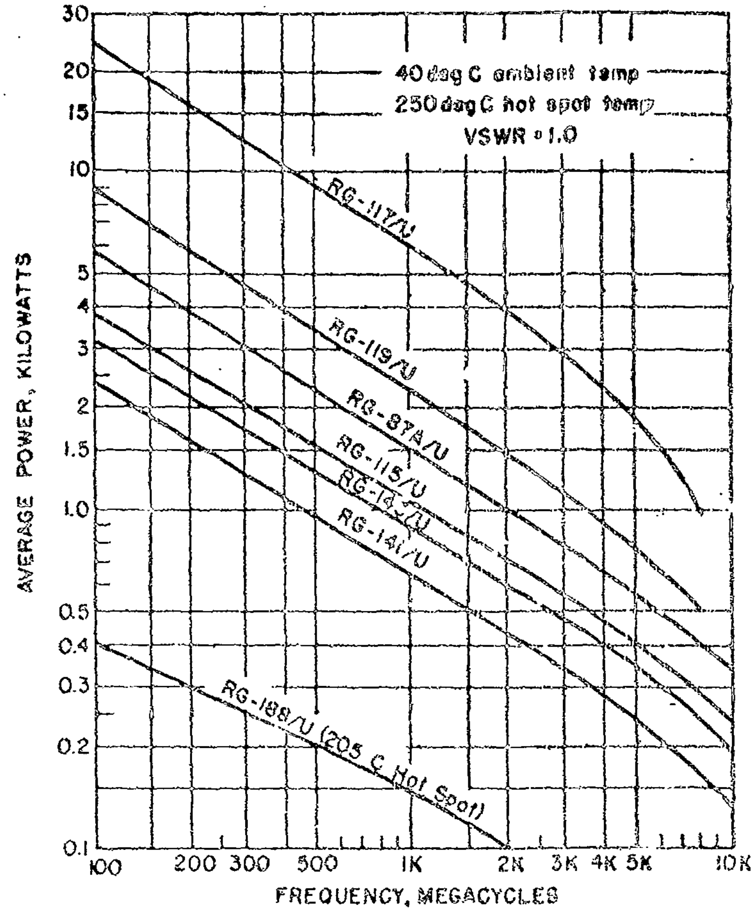


Fig. 8-14. Average power ratings, 50-ohm Teflon cables.

less than 1.3 up to 10 kMc. Their peak voltage rating is limited to 1000 volts for low-duty cycle, pulsed r-f operation. In certain types, this rating can be increased to 4000 volts by sacrificing impedance matching above 3 kMc. Connectors for the large cables such as the LC, LT, and QDL series utilize the dielectric and the conductor of the cable directly. With special precautions, they can be used at the equivalent voltage rating and up to the cutoff frequency of the cable. Matched connectors are also available for the small cables (BNC series) and the miniature cables (MB, SB, and so forth, series). All connectors are wa-

Table 8-13—Low-Capacitance Cables

Type RG-	Maximum capacitance (mmf/ft)	Nominal impedance (ohms)	Inner conductor* (in.)	Dielectric material†	D.O.D. (in.)	O.D. (in.)
62A/U	14.5	93	0.0253	A-2	0.146	0.242
63B/U	11.0	125	0.0253	A-2	0.285	0.405
114A/U	6.8	185	0.007	A-2	0.285	0.405
125/U	7.8	150	0.0159	A-2	0.460	0.6[illegible]
210/U‡	14.5	93	0.0253	F-3	0.146	0.242

* All conductors are of copper-clad steel, except RG-62C which is copper-covered steel.

† A-2 airspaced polyethylene. F-3 airspaced Teflon.

‡ RG-62C has been renumbered as RG-210.

terproof in the mated condition, except for some of the series for small and miniature cables which are used within the interior of equipments. Connectors within any series will also accommodate equivalent 75- and 95-ohm cables. The resultant impedance mismatch is of no practical significance as, in these applications, the total electrical length of the connector is well below 1/20 wavelength.

BALANCED CABLES

Balanced cables consist of two conductors symmetrically spaced and insulated from some reference ground plane or conductor. In most applications, voltages of equal magnitude but opposite polarity are applied to the conductors. While it is a three-wire circuit, because of its symmetry it may be analyzed similarly to the coaxial structure.

Open-Wire Line

The open-wire line is the earliest and simplest form of balanced transmission line. It consists of two hard-drawn copper or copper-clad conductors separated by, or suspended on, rigid insulators. For a given conductor size the center-to-center spacing determines the line impedance Eq. (3). They are most effective at high impedances (300 to 600 ohms) and for low frequencies, particularly with rhombic and doublet antennas. The attenuation and power handling capacity are quite good but are highly dependent on atmospheric conditions and snow or ice loading on the conductors. While installation is simple, it is permanent in nature and requires considerable clearance space around the conductors. Open lines are quite susceptible to interference from external signals and will begin to radiate energy to an appreciable degree when the conductor spacing approaches 1/20 wavelength. Some attempts have been made to overcome these limitations by supporting the two conductors in a rigid tube. However, it is necessary to reduce the spacing between conductors for a practical tube size and the advantages of high impedance are lost. Fabrication difficulties, particularly with connectors, elbow, and similar accessories, also militate against their use.

Twin Lead

Flexible unshielded twin-conductor cables are currently being fabricated with a continuous dielectric of solid or semisolid polyethylene in a variety of cross-sectional configurations. Low in cost, they are very popular for television and FM receivers, radio amateur use, and one type, the RG-86/U, still finds military use. The dielectric increases the attenuation by reducing the impedance range but makes the cable much less sensitive to the weather conditions. Pigmented polyethylene is used to resist cracking caused by continued exposure to the ultraviolet rays of the sun. Care is required in handling these flat cables to prevent kinking, twisting, or uneven tension on the conductors.

Shielded Twin Lead and Dual Coaxial Cables

Greater electrical stability and mechanical ruggedness are obtained with shielded twin-conductor and dual coaxial cables. Two additional parameters, capacitance unbalance and transmission unbalance, are of interest as a measure of electrical dissymmetry. Direct computation or measurement of the capacitance between conductors (C_{12}) is difficult due to variation in ground potentials, proximity effects, and uneven twisting.(32) Instead, it is usually obtained by computation from the individual conductor capacitances as shown in Fig. 8-13.

$$C_{12} = \frac{2(C_1 + C_2) - C_3}{4} \tag{27}$$

The capacitance unbalance (CU) in percent is then defined as

$$\% \, CU = \frac{100\,(C_1 - C_2)}{C_{12}} \tag{28}$$

CU is a measure of any relative variation in conductor diameters, spacing between conductors and shield, and permittivity of the dielectric. In a well-made cable, CU can be kept below 2 percent. CU is independent of frequency over the range where capacitance can be measured directly.

Transmission unbalance (TU) is a much more sensitive parameter and is defined as:

$$TU = \frac{|V_1 - V_2|}{\frac{1}{2}|V_1 + V_2|} \tag{29}$$

where V_1 and V_2 are the vector voltages measured across a matched load when the line is excited by a balanced voltage. (A convenient means of measuring these voltages is described in Paragraph 4.6.18 of MIL-C-17B.) The angular shift (θ) between V_1 and V_2 depends on the phase constant and the total length of the line (ℓ).

$$\theta = (\beta_1 - \beta_2)\,\ell = \omega\ell\,(\sqrt{L_1C_1} - \sqrt{L_2C_2})$$

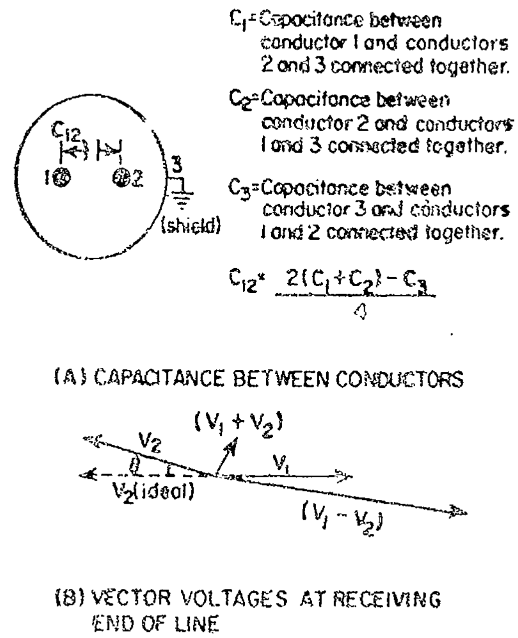


Fig. 8-13. Relationships in a balanced line.

Thus, TU depends on both length and frequency as well as constructional differences. Generally, the variation between inductances is insignificant in comparison with differences in capacitance. While cables with low capacitance unbalance will not assure a low TU, such unbalance may serve as a quick screening test. Empirical correlation has been obtained between these two parameters for RG-22 A/U. (33) Slight differences in attenuation will also be reflected in the values of V_1 and V_2 but these are generally of second order magnitude.

Construction. Shielded twin conductor and dual coaxial cables consist of individually insulated conductors twisted together, filled to the proper diameter, and followed by an overall shield and jacket as shown in Fig. 8-14. The dual coaxial cable has individual shields over each conductor. The parallel construction typified by the RG-23/U is being replaced by cables of circular cross section such as the RG-181( )/U which have greater flexibility and are easier to handle. These cables are mechanically equivalent to coaxial cables of the same overall diameter, and use connectors very similar to the conventional coaxial connectors, except for an additional conductor.

Applications. Twin and dual cables are used primarily for receiver applications at frequencies below several hundred Mc. They are also used extensively in fixed and portable direction-finding antenna systems in which balance is of paramount importance. In such applications, their attenuation characteristics are secondary and power rating is of no concern. A maximum impedance of 95 ohms has been established for twin cables and 135 ohms for dual cables. The dual coaxial is inherently better balanced in the parallel construction, but approaches that of the twin cables when the conductors are twisted. Differences in conductors, particularly their lengths, must be kept to an absolute minimum to achieve the required degree of transmission balance. For example, a phase difference of 3.07 degrees will cause a 5 percent TU which is equivalent to a length difference of only 0.625 inch per hundred feet at 100 Mc, or 0.104 inch at 600 Mc. A summary of the characteristics of the more popular cables appears in Table 8-14.

Small trimmer capacitors can be used at the cable output to improve transmission balance. Even greater improvement, as shown in Fig. 8-15, can be achieved by periodically transposing conductors (that is, connecting conductor 1 of the first length to conductor 2 of the second length to conductor 1 of the third length, and so forth). This procedure would require factory splicing of cables for each specific installation or the use of special polarized fittings at each transposition.

Fig. 8-14. Typical examples of balanced cables.

Table 8-14—Balanced Cable Characteristics

Class	Type RG-	Z_o (ohms)	Capacitance C_{12} (mmf/ft)	CU* (%)	TU† (%)	Construction: Each cond. size	Construction: Diameter over dielectric (in.)	Construction: Overall diameter (in.)	Weight (lb/100 ft)
Unshielded twin conductor	86/U	300 ±10	7.8	--	--	7/0.0285	0.300 × 0.650	0.300 × 0.650	--
Shielded twin conductor	108A/U	78 ±7	24.5	--	--	7/0.0126	0.079 (each)	0.235	--
	22B/U	95 ±5	16.0	3	10	7/0.0152	0.285	0.420	11.0
	111A/U							0.490 (Armor)	14.5
	130/U	95 ±5	17.0	5	10	7/0.0285	0.472	0.625	23.0
	131/U							0.710 (Armor)	29.5
Dual coaxial	23A/U	125 ±5	12.0	--	3	7/0.0285	0.380 (each)	0.650 × 0.945	49.0
	24A/U							0.735 × 1.034 (Armor)	67.0
	181/U	125 ±5	12.0	3	5	0.016	0.210 (each)	0.640	--

* Capacitance unbalance measured on less than 1/40 λ between 1 kc and 1 Mc.

† Transmission unbalance measured on a 100-foot length between 100 and 160 Mc.

Note: Special Navy Cables RG-160/U and RG-182/U were not included as they incorporate additional control wires.

PULSE CABLES

Pulse cables transmit high-voltage direct-current pulses for modulating a microwave magnetron or klystron oscillator. These pulse voltages range from 6 to 25 kw and their peak powers are in the order of megawatts. This imposes much more stringent requirements with respect to corona level, shielding efficiency, and low-frequency attenuation than are required of conventional co-axial cables.

Application

In line-type modulators, the energy stored in the pulse forming network is periodically discharged in the form of a single rectangular pulse by a hydrogen thyratron tube through the cable to the load (that is, the oscillator). For maximum energy transfer, the impedances of the pulse cable and the pulse forming network should be the same, and equal to half the ratio of the peak forward anode voltage and the current of the switching tube. The trend in recent tubes has been toward higher anode voltages and higher currents but to a lower ratio or "effective" impedance. In actual systems, these impedances will vary over a wide range but to keep the number of cables to a minimum, the following ratings have been selected as the preferred values.

Cable Impedance (ohms)	Peak voltage rating (kv)		
50	10	15	20
25		15	20
12-1/2	15	20	30

A slight impedance mismatch is not detrimental, and may even aid in deionization of the thyratron. However, excessive mismatch can result in pulse "echoes" with sufficient energy to prematurely trigger the oscillator.

Construction

Pulse cables have natural, butyl or silicone rubber, or polyethylene as the primary dielectric; with a vinyl, chloroprene, or butyl rubber jacket. The rubber dielectric adheres closely to the conductors under extremes of temperature and mechanical flexing and hence pulse cables do not tend to develop voids as readily as thermoplastic cables. The higher permittivity and dissipation factor of rubber materials are not serious drawbacks in view of the low equivalent frequencies at which they are used. Corona-free operation at these voltages requires some form of conductive layer adjacent to the inner or outer conductor, or both, to equalize localized voltage stresses. Conductive compounds of these materials with

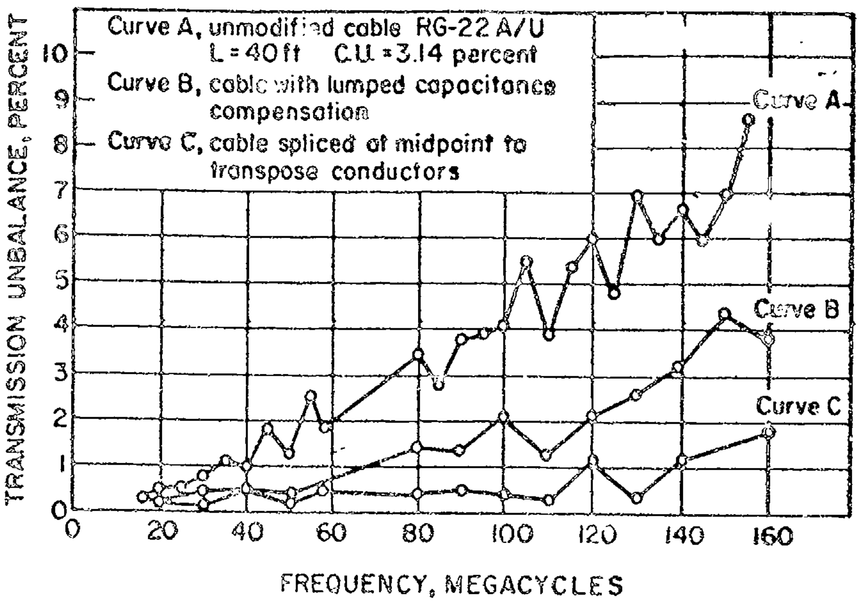


Fig. 8-16. Effect of compensation methods on cable transmission imbalance.

resistivities of 100 to 1000 ohm-cm are extruded or wrapped in a thin layer to conform to the conductor contours and to bond intimately to the dielectric.

Characteristics

Some cables have successfully used polyethylene for moderate powers. (34) However, higher operating temperatures and greater flexibility make rubber dielectrics mandatory in the highest power cables. There is no exact correlation between corona values obtained with 60-cy a-c and unidirectional d-c pulses, although the former has been shown to be more conservative, particularly for polyethylene. (12) It is recommended that the peak pulse voltage be limited to the rms value of the 60-cycle corona extinction voltage until greater operating experience is obtained. This provides an adequate safety factor to allow for corona degradation due to flexing, thermal cycling, and aging. The peak pulse power is established from the amplitude of the pulse voltage in accordance with Eq. (21).

The attenuation and the average power handling capacity under pulse conditions depends directly on the duty cycle which varies between 0.0005 and 0.002 in most radar equipments and is established by the system requirements and limitations on the thyratron and microwave tubes. The energy content of these pulses will be distributed at specific frequencies whose value and amplitude can be determined by a Fourier analysis. From a frequency distribution for an ideal pulse, shown in Fig. 8-16, it can be seen that there is a large d-c component and a major portion of the energy is contained in the frequencies below the first zero. The "weighted average" or rms value of the attenuation for the pulse is represented by the summation of the product of the individual attenuation contributions and the square of the voltage amplitude at each of the discrete frequencies in the Fourier representation. Fortunately, there is very little loss of accuracy by taking only about ten values equally spaced between each zero and omitting everything beyond the fourth or fifth zero. Attenuation data is also required on these cables with sinusoidal frequencies for such rating purposes and for manufacturing control.

The average power applied to the pulse cable is the peak power multiplied by the duty cycle. To determine whether this is within the safe thermal limits of the cable, the "weighted average" attenuation must be used in Eq. (22) to compute the resultant temperature rise. Only limited data are available on pulse cable ratings under varying conditions of pulse width and duty cycle or repetition rate. It is of particular interest for special high-duty cycle applications where thermal heating rather than voltage may be the limiting factor.

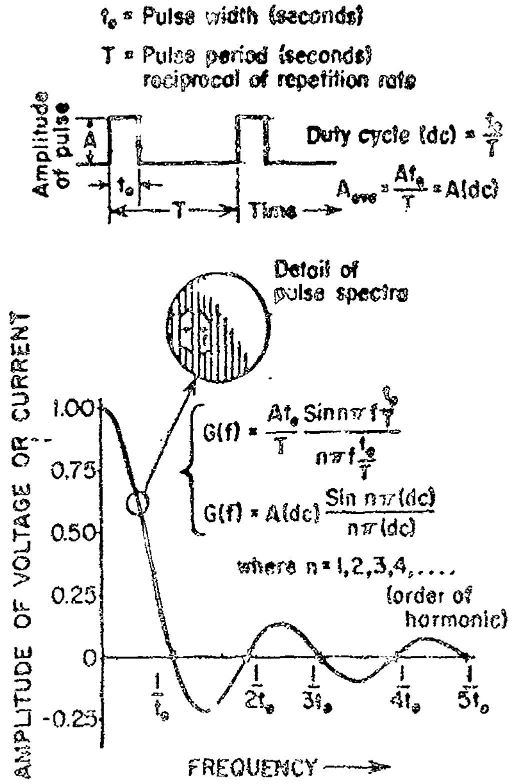


Fig. 8-16. Spectra of a repetitive rectangular pulse.

Shielding

Reduction of spurious electromagnetic radiation or "noise" is of prime concern in view of the very high peak powers involved. More recent pulse cables resort to a triaxial construction in which the outer shield is insulated from the outer or return conductor by an interlayer of polyethylene, Mylar, or silicone impregnated woven glass tapes. The thickness or types of interlayer materials have only a slight effect on shielding, but the capacitance of the interlayer in comparison to that of the cable determines the voltage which the interlayer will have to withstand. The outer conductor consists of an inner copper braid for low attenuation followed by a galvanized steel braid which is effective in reducing low-frequency penetration leakage. A single copper braid is adequate for the outer shield. Figure 8-17 shows the marked improvement in surface transfer impedance (Z_{st}) attained by this construction in contrast to allowing all the braids to be in electrical contact. The curve shown for RG-190/U is with the three braids connected together at both ends of the cable. When connected as a true triaxial, Z_{st} was less than 6 microhms/meter, which was the sensitivity limit of the test equipment. The best manner in which the outer shield should be terminated depends on the length of the cable and the physical and electrical characteristics of the equipment. (35) This triaxial principle has been applied to conventional cables such as the RG-59A and 11A/U by applying another copper braid over the jacket followed by a second vinyl jacket. Such improved shielding is equally effective in preventing external noise from interfering with very low-level signals in the cable.

Pulse Cable Types

Data on pulse cables have been grouped into three categories and summarized in Table 8-15. Group I is the conventional coaxial types consisting of an ozone-resistant insulating compound between layers of conducting compound 15 to 20 mils thick (Type D dielectric). In Type E dielectric, the outer conducting compound is replaced by a red insulating material due to difficulties encountered in clean removal of the conducting compound in the field assembly of connectors. Group II contains cables of triaxial construction with polyethylene as the dielectric and interlayer material with a vinyl jacket. A conducting carbon-loaded polyethylene was required at the interfaces of the conductors except at the center conductor of the RG-156.

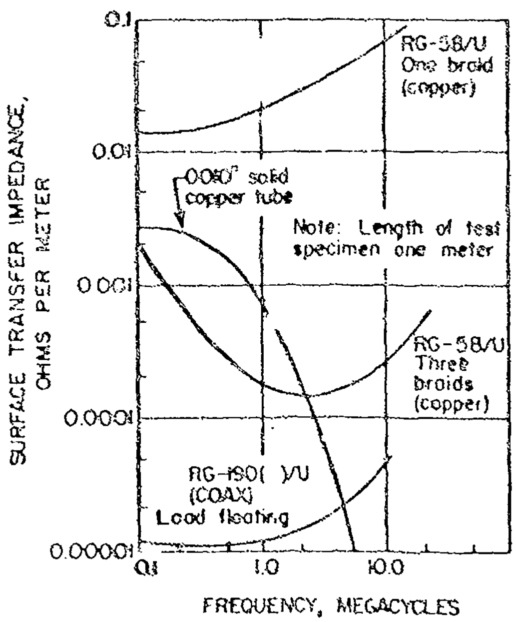


Fig. 8-17. Surface transfer impedances for various shield constructions and frequencies.

Table 8-15—Characteristics of Pulse Cables

Group	Procurement specification	RG-type	Electrical: Z_0 (ohms)	Electrical: Cap. (mmf/ft)	Electrical: Peak voltage (kv)	Mechanical: Conductors (tinned copper	Mechanical: Dielectric* material	Mechanical: D.O.D.‡ (in.)	Mechanical: Braid and shield construction	Mechanical: Overall diameter (in.)	Mechanical: Weight (lbs/100 ft)
I	MIL-C-17	25 / 25A			10	19/0.0117	D / E	0.308 / 0.288	Two tinned copper with cotton separator	0.565 / 0.505	20.5
		26† / 26A†			10	19/0.0117	D / E	0.308 / 0.288	One tinned copper	0.525 / 0.505	18.9
		27†	48	50	15	19/0.0185	D	0.465	One tinned copper	0.650	30.4
		28			15	19/0.0185	D	0.465	Tinned copper, cotton separator, galvanized steel	0.805	37.0
		64 / 64A			10	19/0.0117	D / E	0.308 / 0.288	Two tinned copper	0.495 / 0.475	20.5
		88B			10	19/0.0117	E	0.288	Four tinned copper	0.565	--
II	Dwg SC-C-82969	156	50	30	10	7/0.0284	A	0.285	Tinned copper, galvanized steel; polyethylene interlayer; tinned copper	0.540	--
		157	50	38	15	19/0.0201	A	0.455		0.725	--
		158	25	78	12	37/0.0284	A	0.455		0.725	--
III	Dwg SC-C-32036	190	50	50	20	19/0.0177	H	0.340	Tinned copper, galvanized steel braids; Mylar, silicone glass tape interlayer; tinned copper.	0.700	--
		191	25	86	20	0.470 braid over butyl cord	H	1.000		1.460	--
	Dwg SC-C-32037	192	$12\frac{1}{2}$	175	20	1.055 braid over steel tubing	H	1.650		2.200	--
		193	$12\frac{1}{2}$	160	25		I	1.525		2.100	--
		194	$12\frac{1}{2}$	160	25		I	1.525		1.000	--

*D, E - see text.
A - polyethylene
H - butyl rubber
I - silicone rubber
†Made only with armor outer covering.
‡Diameter over conducting layer when present.

Group III comprises triaxial cables for peak powers between 8 and 50 megawatts and high-duty cycle operation. Higher average powers are achieved in a reasonable size with a dielectric of butyl or silicone rubber, which can withstand center conductor temperatures of 125 and 150 C, respectively. (38) Braided inner conductors are used to retain flexibility in view of their large diameter, dictated by the combination of low impedance and high voltages. (See Fig. 8-18.) RG-194 is identical to RG-193 except that the shielding braid and the rubber jacket have been replaced by an interlocking aluminum armor for improved heat dissipation in interior locations.

The average power handling capacity of Group I and Group II cables is comparable for pulse widths of approximately one microsecond. Group II cables have much lower attenuation at the high frequencies, as shown in Fig. 8-19, which permits much higher average power for extremely short pulses and results in excellent fidelity of the pulse shape. The RG-8A/U cable was included to show the effect of the conducting compound on attenuation above 10 Mc. Pulse rating curves for Group II and III cables are shown in Figs. 8-20 and 8-21 when operated at their rated voltage with an ideal rectangular pulse. Actual pulses more nearly approach a trapezoidal shape for which the power rating increases significantly. If these cables are operated at any combination of duty cycle and pulse width below the curve the average power rating of the cable will not be exceeded. For reduced voltage operation at any given pulse width, the duty cycle can be increased proportionally to the square of the ratio of the rated voltage to the reduced voltage. The maximum d-c current-carrying capacity, as shown in Fig. 8-22, is also of interest to the modulator designer for very high-duty cycle operation.

Connectors

Pulse connectors for Group I cables have been made in either a ceramic or rubber-insert type in accordance with MIL-C-3607. The ceramic types are not corona-free at the full cable voltage, and will occasionally flash over without any permanent harm to the ceramic insert. However, they tend to leak electrical noise due to the poor contact between the mating connector shells. The rubber insert connectors are designed to replace earlier molded versions for the small size cables (RG-25A, 26A, 64A, 88A/U) with an insulating layer under the braid. They have a peak voltage rating of 5 kv at an altitude of 50,000 feet. They may be used with cables utilizing a conducting layer under the braid (RG-25, 26, 64/U) provided extreme care is used in assembly to remove all traces of the conducting material. Improved grounding between the cable shield and mating portions of the connector shell have greatly reduced noise leakage. All connectors are waterproof and capable of field assembly. There is no need for impedance match in pulse connectors.

Connectors for Group II cables and for RG-190/U are similar in general appearance to the rubber-insert type, but are corona free at the rated cable voltages. They are tri-

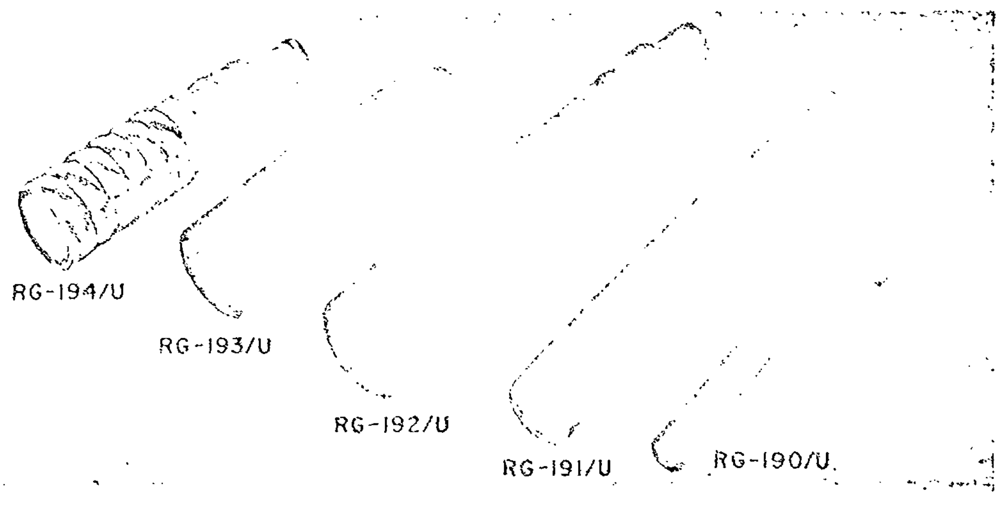


Fig. 8-18. High-power pulse cables.

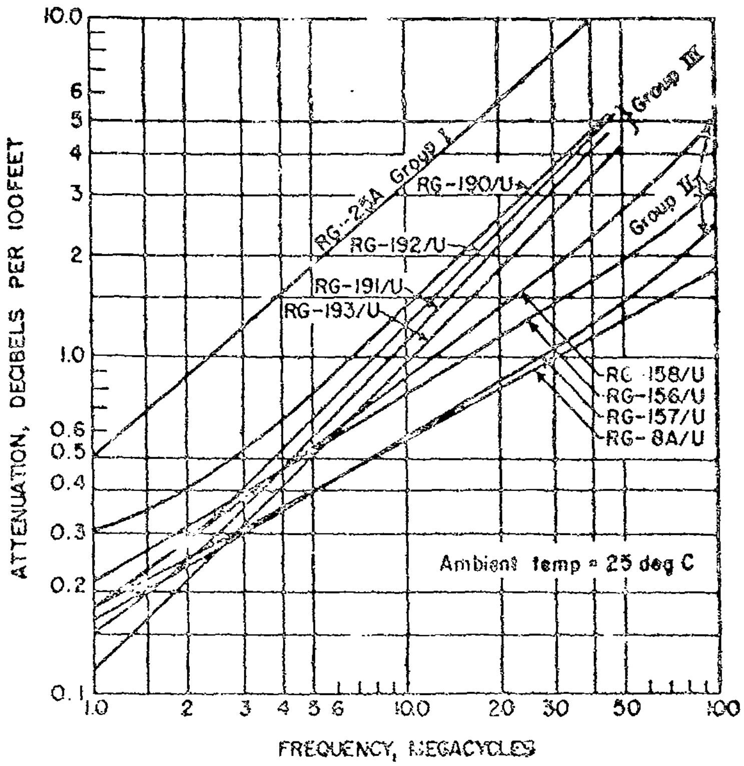


Fig. 8-19. Pulse cable attenuation with sinusoidal voltages.

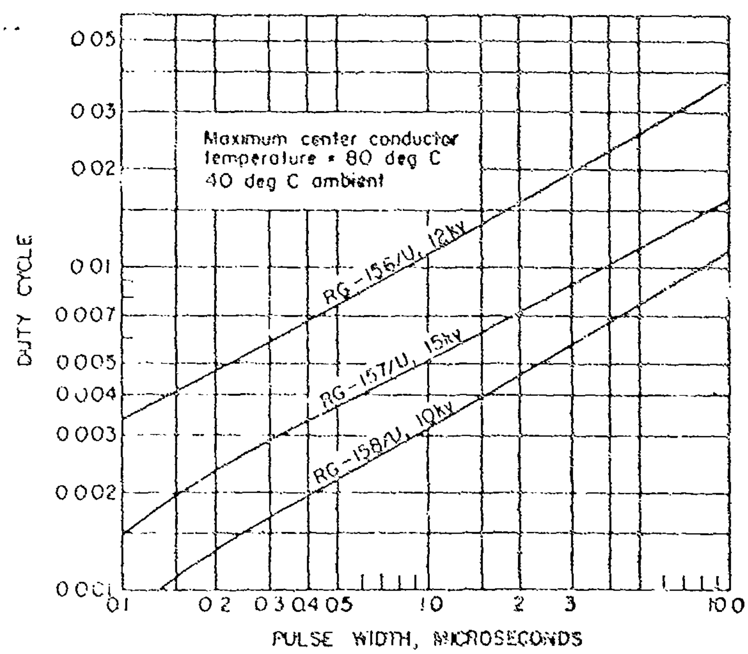


Fig. 8-20. Calculated pulse power ratings, Group II cables.

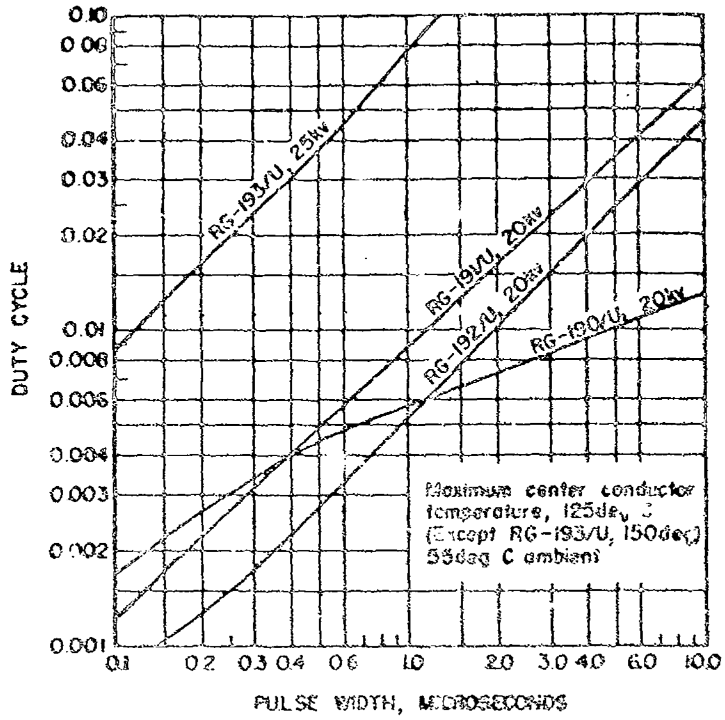


Fig. 8-21. Calculated pulse power ratings, Group III cables.

axial in construction and offer an optional coaxial short between the outer shield and outer conductor as shown in Fig. 8-23. Connectors for RG-191 and RG-192 are presently being developed. They are of the pothead type, in which the prepared cable end will be assembled into a receptacle. It appears necessary to factory mold a butyl rubber sleeve over a portion of the cable core to assure proper assembly and corona-free operation.

SPECIAL PURPOSE CABLES

At times, it is desirable to accentuate certain cable parameters to achieve special performance characteristics. Three such constructional variations which find continued use are described below.

High-Attenuation Cables

These cables have been designed to incorporate the maximum attenuation in a size consistent with their power handling requirements. They are used to interconnect and to achieve isolations of 5 to 20 db between portions of a system to reduce any undesired interaction. They also serve as convenient broadband dummy loads capable of dissipating peak or average powers which are generally beyond the range of most fixed attenuators.

Two such standard 50-ohm cables are the RG-21A/U with a polyethylene dielectric and the RG-126/U with a Teflon dielectric. They achieve their high-attenuation characteristics with high-resistance materials for the inner conductor and also for the outer conductor of the RG-126/U. Increasing the loss in the dielectric is not as desirable because the attenuation becomes more dependent on frequency and the characteristic impedance is not as constant. (37) The salient features of these two cables are shown in Table 8-16.

Delay Cables

Delay cables originated as high-impedance cables, such as the RG-65, for better matching of high-impedance circuits. Their high impedance is achieved by greatly increasing the series inductance of the center conductor which results in phase and attenuation characteristics approaching a low-pass filter. These parameters are comparatively constant with frequency until cutoff is reached, beyond which the attenuation rises and the delay falls off rapidly. The cutoff frequency (f_c) is defined as

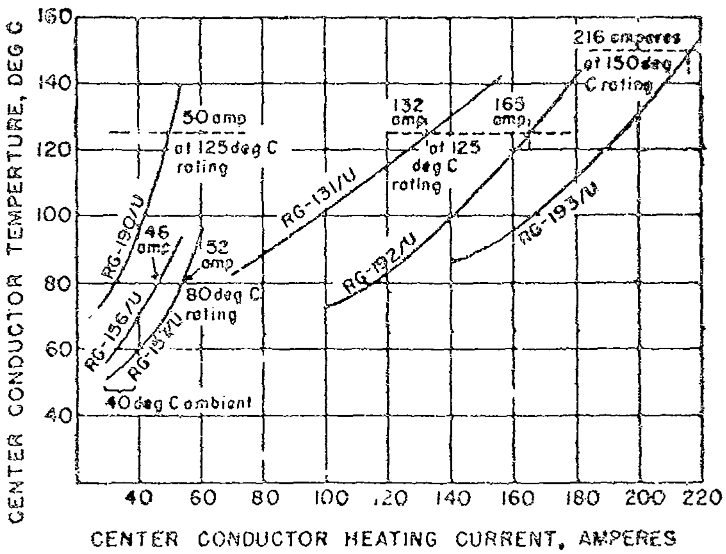


Fig. 8-23. Center conductor temperature rise with heating current, 55 C ambient.

the point where the voltage attenuation is 3 db above the low-frequency value, or the phase shift departs from linearity by some specified percentage. The figure of merit or efficiency of the cable is usually expressed as the ratio of these parameters (that is, decibels per microsecond). Delays of less than a hundredth to 10 microseconds can be achieved with cutoff frequencies from 5 Mc to approximately 100 Mc. These cables are used for pul. forming networks, phase equalization and timing circuits in computers, data transmission, color television, and similar applications. They are also very versatile in the laboratory as their parameters can be adjusted "by the inch."

The center conductor of these cables consists of a fine enameled wire closely spiraled around a polyethylene core. It is followed by a thin taped wrap or extruded dielectric whose thickness determines the capacitance; a braided or served enameled wire outer conductor; and a protective vinyl jacket. To improve the time delay per unit length, the permeability of the core is increased by the incorporation of finely divided magnetic materials. (38) In these types, the magnetic losses generally limit the upper frequency to about 5 Mc, which is adequate for most pulse applications. (The rise time for a rectangular pulse is $0.36/f_c$.) With no magnetic materials present, the cutoff frequency is limited by the capacitance between adjacent turns. It can be extended somewhat by compensating capacitance in the form of "patches" of conducting foil placed under the center conductor spiral. (See Fig. 8-[illegible].) At the present time, compensated cables are available on a limited commercial basis only because of their specialized use and the difficulty of manufacture.

Representative data on delay cables are included in Table 8-17. For critical applications, the characteristic curves of these cables should be examined carefully in the frequency range or pulse width of interest. Some additional improvement in high-frequency response can be achieved by the selection of proper terminating impedance. For low frequencies and short delays, lumped parameter networks are more economical than cable. For delays in the order of milliseconds, ultrasonic types of lines must be used.

Low-Noise Cables

When most cables with a flexible low-loss dielectric are subjected to a sharp impact, twisting, or bending, a spurious signal re-

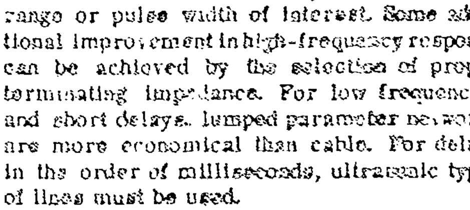


Fig. 5-23. Triaxial pulse plug connector.

Table 8-18—High-Attenuation Cables

Type	RG-21A/U	RG-128/U
Inner conductor (resistive)	[illegible]/0.053	7/0.0203
Core diameter (in.)	0.185	0.1[illegible]
Braid construction	Two, silver-plated copper	One Karma wire
Overall diameter (in.)	0.332	0.280
Minimum attenuation at 0.4 kMc (db/100 ft)	33	46
1.0	51	70
3.0	[illegible]	116
Estimated average power at 0.4 kMc (watts)	39	210
3.0	18	91

sponse of several millivolts can be detected. This "noise" is caused by the "triboelectric" effect, that is, the creation of free electric charges at the metal and dielectric interfaces of the cable due to the local fracture of molecular bonds. (39) This noise voltage can be reduced to virtually zero by interposing a conductive boundary under the shield, preferably of some elastic material, to dissipate the charges. It also can be reduced by terminating the cable in as low a resistive or shunt capacitive load as possible. Requirements for these cables have not been incorporated into MIL-C-17 as yet, but Bureau of Ships Memorandum Serial 817A3-M-1516A establishes a standard measuring method.

Low-noise cables are very similar in construction to the thermoplastic or rubber pulse cables previously described. (40) In fact, RG-35/U cable is exceedingly noise free up to an input impedance of 0.1 megohms. Cables

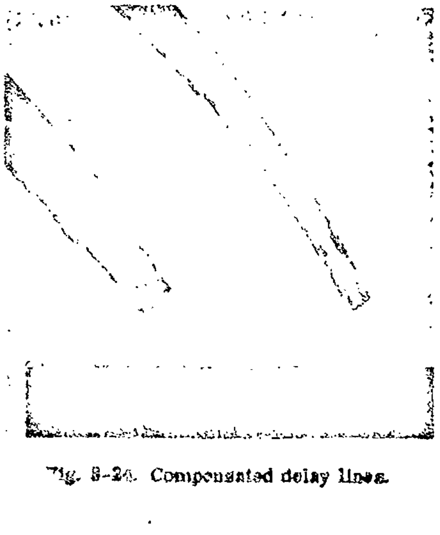


Fig. 8-24. Compensated delay lines.

equivalent in size to RG-8, 11, 59, and 58/U are available for general-purpose use. Miniature cables are required with accelerometers, recording heads, and similar piezoelectric instruments where the cable mass must be kept to an absolute minimum. Such cables vary in overall diameter from 0.50 to 0.120 inch and, except for the conductive coatings, conform to the general constructional practices of the conventional 50-, 75-, and 95-ohm miniature cables. Low-noise cables use standard coaxial connectors of appropriate size.

WAVEGUIDES

BASIC ELECTRICAL CHARACTERISTICS

Modes

Electromagnetic energy can propagate through a hollow metallic tube or waveguide with many possible configurations of electric and magnetic fields; each specific configuration is known as a "mode." The particular mode which is transmitted within a waveguide depends on the excitation employed and on the size and shape of the waveguide cross section in relation to the wavelength or frequency of the wave. Modes are classified in reference to the field components in the direction of energy propagation.

TE (Transverse Electric) Modes. The electric field components are contained in a plane normal to the direction of propagation. As the magnetic field has a component in the direction of propagation, that is, along the waveguide axis, these modes are also called "H" waves.

TM (Transverse Magnetic) Modes. The magnetic field components are contained in a plane normal to the direction of propagation. The

Table 8-17—Comparison of Delay Line Characteristics

Type	RG-65/U	RG-186/U	RG-176	RG-185/U	HH-1500†	HH-1600†	HH-2500†
Mechanical							
Conductor size (in.)	0.008	0.008	0.004	0.0003	0.008	0.004	0.004
Core diameter (in.)	0.110	0.239	0.115	0.115	0.115	0.125	0.125
Core construction and material	Non-magnetic	Nonmagnetic compensated	Magnetic	Magnetic compensated	Magnetic	Magnetic	Magnetic
Over-all diameter (in.)	0.405	0.405	0.405	0.272	0.405	0.280	0.250
Electrical							
Impedance (ohms)	950 ±50	1000 ±50	2240 ±70	2000 ±150	1600	1700 ±250	2800 ±280
Time delay (usec/ft)	0.042	0.20	0.11	1.1	0.073	1.00	0.60
Cutoff frequency (Mc)*	100	60	18	10	5	5	5
Efficiency (db/usec)							
at low freq. (100 kc)	0.98	1.0	0.1	0.3	0.6	0.3	0.2
at cutoff	5.2	16.0	5.0	3.6	6.0	—	1.7
Capacitance mmf/ft	--	--	40	--	48	—	242
D-C resistance (ohms/ft)	7.7	--	—	--	7.7	75	75

* Phase delay departs from linear by more than 5%.

† Marketed by Columbia Technical Sales Corp., New York 32, N.Y.

electric field has a component in the direction of propagation, and for this reason these modes are also called "E" waves.

HEM (Hybrid Electric Magnetic) Mode. This type of mode is a combination of a TE and TM mode, that is, both E and H field components are present in the direction of propagation. Such modes are of particular interest in transmission along dielectrics or dielectric coated rods.

A mode is identified by two numerical subscripts (TE_{mn} or TM_{mn}) which denotes the number of half-wave field variations in the width (a) and height (b) dimensions of the guide. For circular waveguides, cylindrical coordinates are used where m is the variation in the θ direction and n in the ρ direction. For most applications, these dimensions are chosen so that only the dominant mode, that is, lowest frequency or longest wavelength, will propagate. At any abrupt change in the waveguide cross section, or obstacle, higher order modes may be excited, but they are attenuated very rapidly in the dominant mode guide at a short distance from the discontinuity.

The field distribution for various modes in all practical waveguide configurations has been treated extensively. (41) A cross-section view of the more popular modes is illustrated in Fig. 8-25(A) and (B). The direction of the electric vector is also referred to as the type of polarization (vertical, horizontal, circular, and so forth. In the transverse plane, the lines of magnetic flux are always orthogonal to those of the electric field.

Frequency Range

The wave traveling in a guide in any mode is composed of two component plane wave fronts, each traveling at the speed of light (10^8 meters per second). As these waves are at an angle to the direction of propagation, the projection of the free wavelength λ, on the guide axis results in a guide wavelength, λ_g, which is always greater. This gives rise to a phase velocity, V_p, which is close to infinite near the cutoff frequency, and approaches the velocity of light as the frequency is increased. The signal or intelligence travels at a velocity less than that of light, known as the group velocity, V_g. These two velocities are related by the expression:

$$V_p V_g = c^2$$

Propagation cannot occur if the spacing between parallel conducting planes is less than half of the cutoff wavelength, λ_c. The following relationship applies to any mode in an air-filled waveguide.

$$\lambda_g = \frac{\lambda}{\sqrt{1 - (\lambda/\lambda_c)^2}} \qquad (30)$$

In rectangular guides for all TE and TM modes the cutoff wavelength is given by

$$\lambda_c = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}} \qquad (31)$$

For the TE_{10} or dominant mode λ_c reduces to 2a. The cutoff wavelength for the next higher

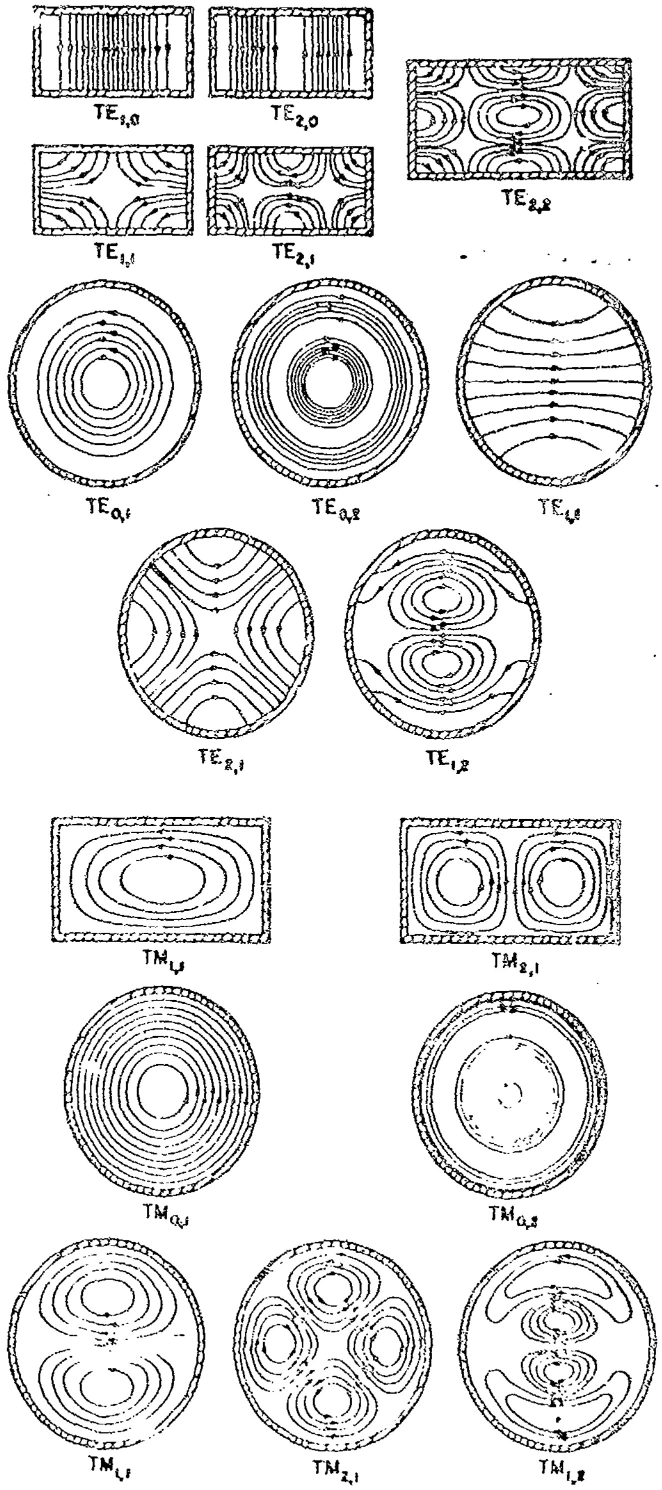


Fig. 8-25. (A) Cross-section view of the configuration of electric field for common TE modes in rectangular waveguides. (B) Cross-section view of the configuration of magnetic field for common TM modes in rectangular and circular waveguides.

mode (TE_{20}) is equal to "a" which results in a theoretical band width for the dominant mode of 2:1 or 66 percent.* It is customary to operate waveguides at frequencies no lower than 10 percent above TE_{10} cutoff due to the rapid increase in attenuation, or 5 percent below the TE_{20} cutoff, to prevent possible mode conversion. (See Fig. 8-26.) In actual practice, rectangular waveguides have a recommended band width which varies between 33.5 and 41.2 percent. The value of "b" must also be kept less than a/2 or $\lambda_c/4$ to prevent initiation of the TE_{m1} or TM_{m1} modes.

For circular guides the cutoff wavelengths are determined by the radius "a" of the guide and the roots of the Bessel function, U_{mn}. Table 8-18 gives the value of λ_c/a for TE_{mn} and TM_{mn} waves. (42) Circular guides have a usable band width of about 30 percent.

Ridged guides achieve a greater band width by increasing the spread between the TE_{01} and the TE_{02} modes. (43) Band widths as high as 4:1 have been achieved in either single- or double-ridge guide whose cutoff characteristics are approximately

$$\lambda_c \approx \frac{\pi(a - s)\,sb}{d} \qquad (32)$$

where

s = width of ridge
d = gap distance in ridge

Once the dimensions of the waveguide have been established, the value of λ_g can be determined for any applied wavelength λ by Eq. (30). This equation may be solved graphically from the quarter-circle chart of Fig. 8-27. It can be seen that λ_g is always greater than λ and approaches infinity near cutoff where λ/λ_c approaches unity. The phase constant is simply $\beta = 2\pi/\lambda_g$.

For wavelengths greater than λ_c, the guide is unable to support a traveling wave and its attenuation increases exponentially with length. Waveguides below cutoff are commonly used for variable attenuators, whose attenuation for a length (L) are shown below:

$$\alpha\,,\,db = 54.5\,\frac{L}{\lambda_c}\,\sqrt{1 - (\lambda_c/\lambda)^2} \qquad (33)$$

For $\lambda >>> \lambda_c$, the attenuation is virtually independent of frequency and

$$\alpha\,,\,db = 54.5\,L/\lambda_c \qquad (34)$$

The input impedance of a waveguide below cutoff is purely reactive.

Attenuation

As in the coaxial line, the attenuation in a waveguide can be separated into conductor and dielectric losses. For a gaseous-filled guide the latter may be neglected except at millimeter wavelengths where absorption phenomena may take place at certain frequencies. The conductor or "wall" losses for a given cross section vary as the square root of the resistivity of the material, and the ratio of applied signal wavelength to the cutoff wavelength. As the wavelength is decreased below the cutoff, the attenuation drops rapidly from its very high initial value to a broad minimum and then rises again slowly as shown in Fig. 8-26. This is true for all rectangular and circular waveguide modes, except for the TE_{0n} circular electric modes (that is, TE_{01}, TE_{02}) whose attenuation continues to decrease with frequency. For minimum attenuation over

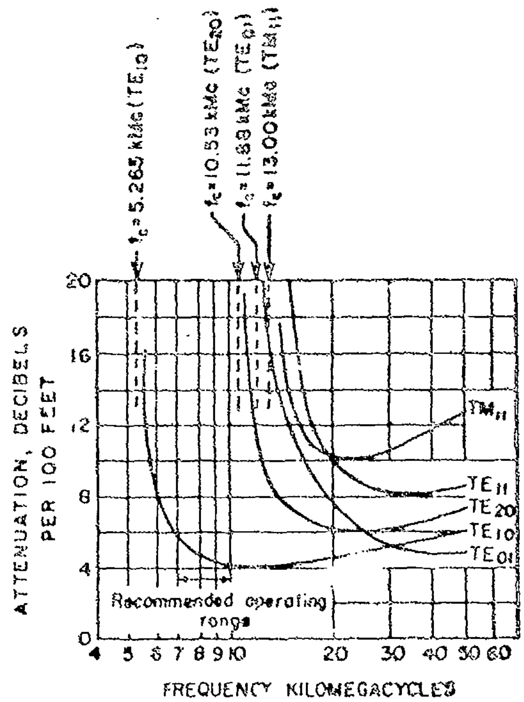


Fig. 8-28. Variation of attenuation with frequency for several modes in RG-51/U waveguide.

* Band widths may be expressed as the ratio of $f_2:f_1$, or as a percentage equal to 200 $(f_1-f_2)/(f_1+f_2)$ where f_1 is the lower frequency and f_2 the upper frequency.

Table 8-18—Normalized Cutoff Wavelengths (λ_c/a) for Circular Guides

Type	n ↓ \ m →	0	1	2
$TE_{m,n}$	1	1.640	3.414	2.057
	2	0.896	1.178	0.937
	3	0.618	0.736	0.631
$TM_{m,n}$	1	2.619	1.640	1.224
	2	1.139	0.896	0.747
	3	0.728	0.618	0.541

the largest possible frequency range, the ratio of a/b should be 2.0 in the dominant mode rectangular guide.

Theoretical formulas for air-filled copper waveguides are given in Table 8-19. These may be converted to metals of other electrical conductivities by multiplying them by the inverse ratio of the square root of the conductivities shown in Table 8-20. Actual values of attenuation are dependent on microscopic surface conditions as the frequency is increased and the skin depth is reduced to thousandths of an inch. Up to 15 kMc the measured values are generally within 25 percent of the theoretical, with the best correlation being obtained on drawn surfaces. Machined surfaces are frequently poorer and plated surfaces vary a great deal due to porosity and roughness. In the vicinity of 35 kMc the attenuation can rise from 60 to 110 percent above theoretical and deteriorate even further under adverse environmental conditions. (44) Thin oxides or chemical coatings are not harmful if their resistivity is high, that is, as long as they are good dielectrics.

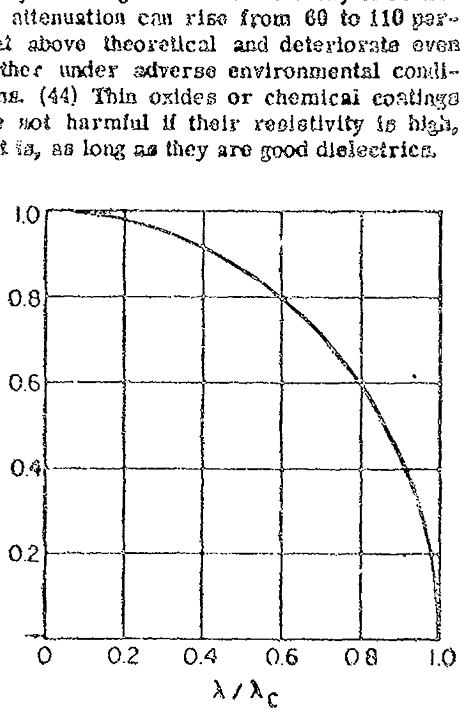


Fig. 8-37. Chart for determining waveguide wavelength.

Characteristic Impedance

The absolute value of the characteristic impedance of a waveguide is of little direct concern, as most associated items are normalized with respect to it. It may be defined in three ways for a matched lossless rectangular waveguide in the TE_{01} mode. Similar definitions exist for other types of waveguides.

1. $Z_{(w,v)} = V^2/W$, where V is the rms value of the electric voltage at the midpoint of the broad walls, and W is the total power flowing down the guide.

2. $Z_{(w,i)} = W/I^2$ where I is the rms value of the longitudinal current flowing on one wall normal to the electric vector, and W is the total power flowing down the guide.

3. $Z_{(v,i)} = V/I$, is the geometric means of $Z_{(w,v)}$ and $Z_{(w,i)}$ above.

The third definition above leads directly to the "wave impedance" which is the ratio of the transverse components of the electric and magnetic fields at any point of the waveguide.

$$Z_{wave} = \frac{V}{I} = \frac{E_t}{H_t}$$

For propagation in air in the TEM mode, this reduces to the so-called "impedance of free space."

$$Z_{TEM} = \eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 377 \text{ ohms}$$

For all TE and TM modes the wave impedances for air-filled guides are given by

$$Z_{TE} = \eta_0 \frac{\lambda_g}{\lambda} \text{ or } \frac{\eta_0}{\sqrt{1 - (\lambda/\lambda_c)^2}} \quad (35)$$

$$Z_{TM} = \eta_0 \frac{\lambda}{\lambda_g} \text{ or } \eta_0 \sqrt{1 - (\lambda/\lambda_c)^2} \quad (36)$$

These expressions are useful in the determination of impedance mismatch and VSWR where the guide dimensions are changed slightly, without any abrupt discontinuities.

Power Capacity

The power handling capability of a waveguide is determined by the breakdown of the gaseous dielectric in the vicinity of maximum electric stress. The gaseous discharge process is

Table 8-19—Attenuation and Power Formulas for Common Waveguide Types

Type of guide mode	λ_c	Attenuation (α)* (nepers per meter $\times 10^{-9}$)	CW power† (Mw)	Location of maximum voltage stress
TE_{10} (Rectangular)	2a	$\frac{1.40A}{a}\left(\frac{a}{2b}+\frac{\lambda^2}{\lambda_c^2}\right)$	$0.0663\,ab\frac{\lambda}{\lambda_g}E^2$	At a/2, parallel to direction of b
TE_{11} (Circular)	3.41a	$\frac{0.70A}{a}\left(0.415+\frac{\lambda^2}{\lambda_c^2}\right)$	$0.199\,a^2\frac{\lambda}{\lambda_g}E^2$	At center of guide
TE_{01} (Circular)	1.64a	$\frac{0.70A}{a}\left(\frac{\lambda}{\lambda_c}\right)^2$	$0.199\,a^2\frac{\lambda}{\lambda_g}E^2$	At radius equal to 0.48a
TM_{01} (Circular)	2.78a	$\frac{0.70A}{a}$	$0.769\frac{a^4}{\lambda^2}\frac{\lambda^2}{\lambda_g}E^2$	$a/\lambda < 0.701$—at center of guide
			$0.333\,a^2\frac{\lambda_g}{\lambda}E^2$	$a/\lambda > 0.701$—at radius equal to 0.765a

All dimensions in meters, a = width of rectangular guide, or radius of circular guide and b is the height of rectangular guide.

* $A = \frac{\sqrt{c/\lambda}}{\sqrt{1-(\lambda/\lambda_c)^2}}$ for copper walls with air dielectric.

† E is peak voltage expressed in kv per meter.

more variable in a waveguide than a coaxial line due to the nonuniform field distribution, the large gap distances, and the frequency of the applied energy which approaches the transit time of the electrons for the gap spacings involved. Breakdown is a primary concern under pulsed conditions as the continuous wave (CW) power available from tubes is considerably below the capacity of the waveguide. While heating occurs due to resistive losses in the walls, it is not sufficient to cause any significant temperature rise or any power limitations.

Breakdowns or continuous discharge occurs when free electrons are produced in the gap at a rate which exceeds their removal by diffusion to the surrounding walls or attachment to neutral gas molecules. This process starts by the chance appearance of a free electron, its acceleration by the electric field to produce ionizing collisions, the buildup of a positive-ion space charge, and finally the creation of sufficient electrons to permit a gaseous discharge. Whether an electron is effective in starting this process will depend upon its initial position and velocity, and the phase of the microwave field at the time of its appearance. When a single pulse is applied, sufficient time may not exist for breakdown to occur. As the pulse width is decreased below about 1 microsecond at atmospheric pressure, the maximum electric field can be increased significantly. For a series of pulses, the breakdown value is lowered as some electrons will remain from preceding pulses, and eventually a pulse will occur in which breakdown can take place. Thus, the single pulse condition imposes an upper limit and the CW condition a lower limit on the magnitude of the breakdown field. The value for a series of pulses would be between these

Table 8-20.—Characteristics of Common Waveguide Metals

Metal composition	Resistivity (ohm-cm $\times 10^{-6}$)	Conductivity (% IACS)*
Silver	1.63	106.4
Copper	1.724	100.0
Tellurium copper	1.90	91.0
Coin silver	2.10	82.0
Aluminum	2.83	60.9
Brass (90-10)	4.22	40.0
Magnesium	4.60	37.5
Brass (66-34)	7.00	24.6

* International Annealed Copper Standard

limits depending on the pressure and pulse characteristics. It has been shown that the single pulse condition can be used when the repetition rate is less than approximately three times the pressure expressed in millimeters of mercury (normal atmospheric pressure ≈ 760 mm). (45)

Many of the factors discussed above are statistical in their behavior, and in the experimental determination of breakdown, data are usually expressed as a probability of occurrence at a particular power level. Breakdown probability is defined as the ratio of pulses during which breakdown occurs, to the total number of pulses applied. This may be projected to a very small but finite probability known as the "onset" stress, which determines the rating of waveguide components. Testing time may be reduced by the introduction of a source of energy radiation (X-rays, gamma rays, ultraviolet light, and so forth) to enhance the production of free electrons beyond that provided by normal background X-ray or cosmic ray radiation.

Expressions for the CW power and location of the maximum field stress for the most popular modes are shown in Table 8-19. The peak value of voltage (E) depends on the modulation and VSWR in a manner similar to the coaxial case. Breakdown is most likely to occur where the field is distorted due to abrupt changes of cross section, conversion to other modes, or resonances. Surface roughness or chemical coatings on the waveguide walls will also influence the breakdown value.

DETAILED DISCUSSION OF TYPES

Rectangular Waveguides

Standard rectangular waveguides are available over the frequency range from 470 Mc to 326 kMc with inside dimensions extending from 15.00 by 7.50 inch to 0.0340 by 0.017 inch. Military procurement is in accordance with MIL-W-85C, "Tubing, Waveguide, Seamless, Rectangular," and the requirements therein are closely paralleled by EIA Standard TR-108A, "Rectangular Waveguides." The latter includes two series of waveguide sizes. Each series provides a continuous frequency coverage that is displaced in frequency by half of a waveguide band from the other series; that is, the end points of the "A" series are the mid-points of the "B" series. The military services have agreed that when additional waveguide sizes are required in the future they will be selected from the EIA Standard.

Construction. Early waveguides were fabricated from copper or brass architectural tubing whose outside dimensions had a width to height or aspect ratio of 2:1 (that is, 1 by 1/2 inch, 1/2 by 1/4 inch., and so forth). These early sizes have been retained, and it is still common practice to refer to waveguide sizes by their outside dimensions. All new guides utilize an aspect ratio of 2:1 for the inside dimensions which simplifies scaling of designs from one guide size to another. Table 8-21 summarizes the dimensions and frequency range for the EIA Standards and those sizes and constructions which have been assigned military nomenclature. The EIA designation consists of the letters WR (waveguide rigid) followed by a number equal to the broad wall dimension in hundredths of an inch. For the extreme high-frequency region (that is, millimeter wavelengths) the outside configuration of all the waveguides is made circular at a constant diameter of 0.156 ± 0.001 inch for greater rigidity and simplicity of fabrication. Data for these special millimeter waveguides are contained in Table 8-22.

Rectangular waveguides are also supplied in several variations of these dimensions for special applications. Where sections of waveguides are to be used for fabrication of associated devices, precision tubing can be obtained with a maximum tolerance of ±0.002 inch in any dimension in the RG-49, 50, and 51/U sizes, and with a maximum tolerance of ±0.001 inch in the RG-52, 91, and 53/U sizes. Where two to three atmospheres of internal pressure are required for high power use, or for high external pressure such as encountered in submarine use, tubing with heavy and extra heavy wall thicknesses are available to limit deformation of the broad wall. Where space is at a premium and at low power levels, waveguides with reduced heights are used with some slight increase in attenuation. Thin-wall versions of RG-69/U have also been made in brass and copper-clad stainless steel to reduce weight for long runs on shipboard masts.

Materials. A variety of construction techniques and materials are required to encompass this broad range of sizes and frequencies. In the middle-size range (WR650 to WR42) drawn tubing of alloys of copper, aluminum, or magnesium are very popular. The copper alloy known as commercial bronze (90-percent copper, 10-percent zinc) has good mechanical properties, is easy to solder or braze, is reasonably corrosion resistant, and is not subject to failure by season cracking.

Table 8-21 —Dimensions, Tolerances and Frequency Range for Rigid Rectangular Waveguides

RG-( )/U				EIA designation	Frequency range (kMc) for dominant (TE_{10}) mode	Dimensions in inches								Maximum inner radius*
						Inner dimensions			Outer dimensions			Wall thickness		
Brass	Silver	Aluminum	Magnesium			a	b	Tolerance	c	d	Tolerance	Nominal	Deviation from mean	
				WR1500	0.47-0.75	15.000	7.500	±0.015	--	--	--	--	--	--
				WR1150	0.064-0.096	11.500	5.750	±0.015	--	--	--	--	--	--
				WR975	0.75-1.12	9.750	4.875	±0.010	10.000	5.125	±0.010	0.125	±0.010	3/64
				WR770--	0.96-1.45	7.700	3.850	±0.005	7.950	4.100	±0.005	0.125	±0.005	3/64
69		103		WR650--	1.12-1.70	6.500	3.250	±0.005	6.660	3.410	±0.005	0.080	±0.005	3/64
				WR510--	1.45-2.20	5.100	2.550	±0.005	5.260	2.710	±0.005	0.080	±0.005	3/64
104		105		WR430--	1.70-2.60	4.300	2.150	±0.005	4.460	2.310	±0.005	0.080	±0.005	3/64
112		113		WR340--	2.20-3.30	3.400	1.700	±0.005	3.560	1.860	±0.005	0.080	±0.005	3/64
48		75	167	WR284--	2.60-3.95	2.840	1.340	±0.005	3.000	1.500	±0.005	0.080	±0.005	3/64
				WR229--	3.30-4.90	2.290	1.145	±0.005	2.418	1.273	±0.005	0.064	±0.005	3/64
49		95	168	WR187--	3.95-5.85	1.872	0.872	±0.005	2.000	1.000	±0.005	0.064	±0.005	1/32
				WR159--	4.90-7.05	1.590	0.795	±0.004	1.718	0.923	±0.004	0.064	±0.005	1/32
50		106	163	WR137--	5.85-8.20	1.372	0.622	±0.004	1.500	0.750	±0.004	0.064	±0.005	1/32
51		68	170	WR112--	7.05-10.00	1.122	0.497	±0.004	1.250	0.625	±0.004	0.064	±0.005	1/32
52		61	171	WR90--	8.20-12.40	0.900	0.400	±0.003	1.000	0.500	±0.003	0.050	±0.005	1/32
				WR75--	10.00-15.00	0.750	0.375	±0.003	0.850	0.475	±0.003	0.050	±0.005	1/32
91	107		172	WR62--	12.4-18.00	0.622	0.311	±0.0025	0.702	0.391	±0.003	0.040	±0.003	1/64
				WR51--	15.00-22.00	0.510	0.255	±0.0025	0.590	0.335	±0.003	0.040	±0.003	1/64
53	66	121	173	WR42--	18.00-26.50	0.420	0.170	±0.0020	0.500	0.250	±0.003	0.040	±0.003	1/64
				WR34--	22.00-33.00	0.340	0.170	±0.0020	0.420	0.250	±0.003	0.040	±0.003	1/64
	96			WR28--	26.50-40.00	0.280	0.140	±0.0015	0.360	0.220	±0.002	0.040	±0.003	1/64
	97			WR22--	33.00-50.00	0.224	0.112	±0.0010	0.304	0.192	±0.002	0.040	±0.003	0.010
				WR19--	40.00-60.00	0.188	0.094	±0.0010	0.268	0.174	±0.002	0.040	±0.003	0.010
	98			WR15--	50.00-75.00	0.148	0.074	±0.0010	0.228	0.154	±0.002	0.040	±0.003	0.008
	99			WR12--	60.00-90.00	0.122	0.061	±0.0005	0.202	0.141	±0.002	0.040	±0.003	0.006
				WR10--	75.00-110.00	0.100	0.050	±0.0005	0.180	0.130	±0.002	0.040	±0.003	0.006

* For all sizes: Minimum outer radius 1/64 inch
Maximum outer radius 1/32 inch

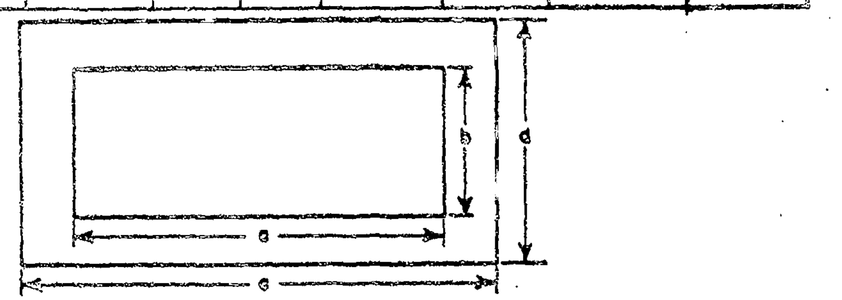


Table 8-22—Millimeter Rectangular Waveguides

Military nomenclature* RG-	Operating range for TE_{10} mode frequency (kMc) (f_1 to f_2)	Width (a)	Height (b)	Dimensional tolerance (in.)	Maximum eccentricity†	Maximum inner corner	Theoretical attenuation (db/ft) (f_1 to f_2)	CW power rating‡ (kw) (f_1 to f_2)
138/U	90.0-140.0	0.0800	0.0400	±0.003	0.001	0.0031	1.52-0.99	1.8-2.0
136/U	110.0-170.0	0.0650	0.0325	±0.00025	0.001	0.0015	1.63-1.37	1.2-1.7
135/U	140.0-220.0	0.0510	0.0255	±0.00025	0.001	0.0015	3.08-1.93	0.71-1.07
137/U	170.0-260.0	0.0430	0.0215	±0.00020	0.0005	0.0015	3.84-[illegible].54	0.52-0.73
139/U	220.0-325.0	0.0340	0.0170	±0.00020	0.0005	0.0015	5.12-3.48	0.35-0.47

* There are no EIA types in this size range.

† Half the difference between opposite wall thicknesses measured at any cross section perpendicular to the longitudinal axis.

‡ E_{max} = 15 kv/cm.

Oxygen-free high-conductivity copper (OHFC) has increased use since it has a lower initial attenuation and a greater stability than commercial bronze even when the latter is silver plated. For example, the attenuation of WR137 will vary between 2.00 and 2.40 db per hundred feet for OHFC copper, 2.80 and 3.38 for brass, and 2.44 and 2.95 for aluminum. The drawing process for brass and copper tubing produces smooth nonporous surfaces with an attenuation very close to theoretical up to approximately 10 kMc. Silver plating of brass components is effective in reducing attenuation provided the surfaces are buffed, electropolished, or applied by the "periodic reverse" process to minimize porosity. Unfortunately, some of the silver corrosion products are poor dielectrics and will cause an appreciable increase in losses as the frequency is increased (that is, as the skin depth more nearly approaches the thickness of the corrosion layer). A thin "flash" coating of rhodium, palladium, or gold will minimize the effect of aging. Plating on the interior surfaces of long sections of waveguide tubing should be avoided as normal commercial processes will result in a thin, nonuniform coating. While adequate plating thickness can be achieved with internal anodes and a periodic reverse process, it is not economical for long lengths of tubing.

Where weight is concerned, 2S aluminum alloy or FS-1 magnesium alloy is used. Both of these alloys exhibit a high strength-to-weight ratio, ready availability, adaptability to various fabrication techniques, and reasonable compromise of electrical characteristics. Magnesium affords about a 40 percent reduction in weight and 28 percent increase in strength in comparison to aluminum in WR112 size. (46)

In contact with moist air both materials develop a thin grey protective film of hydrated oxides and carbonates which tends to protect them against further corrosion. To reduce galvanic corrosion in the presence of water or other electrolytic solutions, aluminum surfaces are anodized and magnesium surfaces are treated with sodium dichromate coatings, in accordance with Specification MIL-C-5541 "Chemical Films for Aluminum and Aluminum Alloys" and Specification MIL-M-3171 "Magnesium Alloy, Process for Corrosion Protection of," respectively. Exterior surfaces should receive additional coatings of irridite or chromate primers followed by two coats of enamel, in accordance with the procedures outlined in Specification MIL-F-14072 "Finishes for Ground Signal Equipment." Aluminum constructions also predominate for sizes above the WR650. It is more economical in these larger sizes to construct the waveguide from various U-shaped sections or flat plates bolted together which accounts for the inability to standardize on outside dimensions as shown in Table 8-21.

Where minimum attenuation is required, coin silver (90 percent silver, 10 percent copper) is used for the WR62 size and smaller. Coin silver may comprise the entire thickness of the wall or serve as an inner laminating material with an outer sheet of inexpensive ductile metal such as brass. The extremely small sizes, RG-135 to 139/U, must be electroformed on highly polished precision mandrels to ensure that interior surfaces approach a mirror-like finish (surface roughness of less than 10 microinches rms). Coin silver surfaces age poorly in a manner similar to silver plate.

Electrical Characteristics. Data on the theoretical attenuation and cw power rating are tabulated in Table 8-23 for standard waveguides operating in the dominant mode. The power rating is based on a breakdown strength of air of 15 kv per cm at normal atmospheric pressure which provides a safety factor of about 4. Figure 8-38 is an overall plot of how these parameters vary with waveguide dimensions and permits an approximation for those waveguides not included in Table 8-23.

Increased band widths can be achieved in rectangular waveguides by departure from the optimum aspect ratio of 2:1 at some sacrifice in attenuation and power handling capacity. Two such waveguides, shown in Table 8-24, have an aspect ratio of 2.8:1 which serves to increase the frequency at which the TE_{01} mode can be initiated. Even broader band widths can be obtained in a "flat" waveguide by choosing the dimensions so that higher order modes of only the TE_{m0} type may propagate. However, care must be taken in the design of components to avoid coupling to the other modes (TE_{20} and TE_{30}) which can cause large losses and excessive distortion. Such waveguides, capable of supporting several modes, generally utilize mode filters to dissipate the energy in the undesired modes by conductive or resistive elements appropriately situated in the waveguide. One such waveguide with internal dimensions of 0.740 by 0.140 inch operates successfully over the range of 10 to 40 kMc. It exhibits an attenuation of 0.34 to 0.35 db per meter and a power rating of 60 to 160 kw over this frequency range. This is approximately equivalent to the characteristics of the middle size of the four waveguides it replaces.

Circular Waveguides

Circular waveguides have not received the wide usage of rectangular waveguides in the past except as part of rotary joints of transitions which required circular symmetry. Their use is steadily increasing, particularly in light of the greater interest in the higher and higher frequencies. The proposed series of circular waveguide sizes which are shown in Table 8-25 are being standardized jointly by EIA and the Military Services. For each size guide, the frequency range is indicated for the TE_{11} and TE_{01} mode of operation. For each mode, the band width is about 30 to 35 percent; with recommended limits of operation between 1.15 TE_{11} to 0.92 TE_{21}, and 1.31 TE_{01} to 0.91 TE_{02}, respectively. In

Table 8-23—Electrical Properties of Rectangular Waveguides

Military nomenclature RG–	Material (alloy)	Theoretical attenuation (db/100 ft) (f_1 to f_2)	CW power* rating (Mw) (f_1 to f_2)
69/U	Brass	0.317-0.212	10.0-14.5
103/U	Aluminum	0.269-0.178	
104/U	Brass	0.588-0.385	4.38-6.30
105/U	Aluminum	0.501-0.330	
48/U	Brass	1.102-0.752	1.82-2.60
75/U	Aluminum	0.940-0.641	
49/U	Brass	2.08-1.44	0.800-1.15
95/U	Aluminum	1.77-1.22	
50/U	Brass	2.87-2.30	0.475-0.625
106/U	Aluminum	2.45-1.94	
51/U	Brass	4.12-3.21	0.310-0.410
68/U	Aluminum	3.50-2.74	
52/U	Brass	6.45-4.48	0.182-0.275
67/U	Aluminum	5.49-3.83	
91/U	Brass	9.51-8.31	0.110-0.150
107/U	Aluminum	6.14-5.36	
53/U	Brass	20.7-14.8	
66/U	Silver	13.3-9.5	0.040-0.060
121/U	Aluminum	17.6-12.6	
96/U	Silver	21.9-15.0	0.024-0.036
97/U	Silver	31.0-20.9	0.016-0.022
98/U	Silver	52.9-39.1	0.0073-0.011
99/U	Silver	93.3-52.2	0.0050-0.0072

* E_{max} = 15 kv/cm

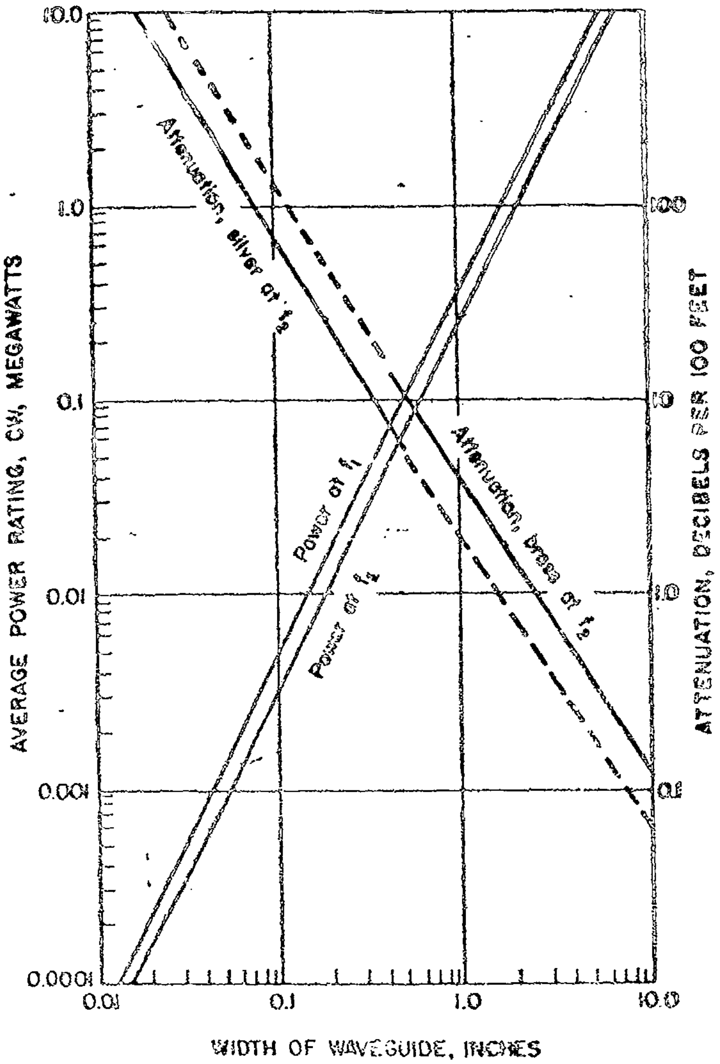


Fig. 8-33. Variation of parameters of rectangular waveguide (TE_{10} mode) with dimensions.

actual practice the usable band width may be limited to 10 or 15 percent due to the large variation of attenuation with frequency.

Modes. Each mode of operation has particular advantages in so far as the transmission line and the system requirements are concerned. The TE_{11} mode in circular guide is the dominant mode analagous to the TE_{10} mode in a rectangular guide.* However, it is difficult to maintain a fixed direction of polarization in long runs of circular guide if irregularities occur in the cross section. The attenuation characteristics vary in a similar manner to that of the rectangular guide. For

* Analagous waves for rectangular and circular guides do not have the same subscripts. A comparison of Fig. 8-25 will also show that the TM_{11} wave in rectangular guide is analagous to the TM_{01} wave in circular guide; the TM_{12} rectangular is analagous to the TM_{02} circular, and so on.

Table 8-24—Special 2.0:1 Rectangular Waveguides

Military nomenclature*	Internal dimensions (in.)	Operating range (Mc)
RG-109/U	2.840 × 1.000	2600-5850
RG-110/U	1.372 × 0.497	5850-13,400

* In accordance with Navy Drawing RE 49A513.

Table 8-25—Dimensions, Tolerances, and Frequency Range for Rigid Circular Waveguides

EIA designation	Frequency range (kMc) TE_{01} mode	Frequency range (kMc) TE_{11} mode	Nominal I.D. (in.)	Nominal O.D. (in.)	Nominal wall thickness (in.)	Tolerance on average I.D. (plus & minus) (in.)	Wall thickness tolerance (plus & minus) (in.)	I.D. out-of-roundness (in.)	Nominal fraction I.D. (in.)
WC 2551--	0.603-0.840	0.312-0.427	25.508			0.038		0.035	
WC 2179--	0.709-1.10	0.365-0.500	21.791			0.023		0.032	
WC 1862--	0.936-1.29	0.427-0.586	18.616			0.020		0.019	
WC 1590--	1.10-1.51	0.500-0.686	15.903			0.015		0.016	
WC 1359--	1.28-1.77	0.586-0.803	13.585			0.013		0.014	
WC 1161--	1.50-2.07	0.686-0.939	11.606			0.010		0.012	
WC 992--	1.76-2.42	0.803-1.10	9.915			0.010		0.010	
WC 847--	2.06-2.83	0.939-1.29	8.470	8.630	0.080	0.008	0.006	0.008	
WC 724--	2.41-3.32	1.10-1.51	7.235	7.395	0.080	0.007	0.006	0.007	
WC 618--	2.82-3.89	1.29-1.76	6.181	6.341	0.080	0.006	0.005	0.006	
WC 528--	3.30-4.56	1.51-2.07	5.280	5.440	0.080	0.005	0.004	0.005	
WC 451--	3.86-5.32	1.76-2.42	4.511	4.671	0.080	0.005	0.003	0.005	
WC 385--	4.52-6.22	2.07-2.83	3.853	4.013	0.080	0.004	0.004	0.003	
WC 329--	5.29-7.28	2.42-3.31	3.292	3.452	0.080	0.003	0.003	0.003	
WC 281--	6.19-8.53	2.83-3.88	2.812	2.942	0.065	0.003	0.004	0.003	
WC 240--	7.25-9.98	3.31-4.54	2.403	2.533	0.065	0.0025	0.005	0.002	
WC 205--	8.51-11.7	3.89-5.33	2.047	2.177	0.065	0.002	0.004	0.002	2-3/64
WC 175--	9.95-13.7	4.54-6.23	1.750	1.880	0.065	0.0015	0.003	0.0015	1-3/4
WC 150--	11.6-16.0	5.30-7.27	1.500	1.630	0.065	0.0015	0.003	0.0015	1-1/2
WC 128--	13.6-18.7	6.21-8.51	1.281	1.411	0.065	0.0013	0.0025	0.0013	1-9/32
WC 109--	15.9-21.9	7.27-9.97	1.094	1.194	0.050	0.001	0.002	0.0011	1-3/32
WC 94--	18.6-25.6	8.49-11.6	0.938	1.038	0.050	0.0009	0.002	0.0009	15/16
WC 80--	21.9-30.1	9.97-13.7	0.797	0.897	0.050	0.0008	0.0015	0.0008	51/64
WC 69--	25.3-34.9	11.6-15.9	0.688	0.788	0.050	0.0007	0.0015	0.0007	11/16
WC 59--	29.3-40.4	13.4-18.4	0.594	0.674	0.040	0.0006	0.001	0.0006	19/32
WC 50--	34.3-48.0	15.9-21.8	0.500	0.580	0.040	0.0005	0.001	0.0005	1/2
WC 44--	39.9-54.9	18.2-24.9	0.438	0.518	0.040	0.00045	0.001	0.0004	7/16
WC 38--	46.6-63.9	21.2-29.1	0.375	0.455	0.040	0.00038	0.001	0.0004	3/8
WC 33--	53.1-73.1	24.3-33.3	0.328	0.393	0.030	0.00033	0.001	0.0003	21/64
WC 28--	61.9-85.2	28.3-38.8	0.281	0.341	0.030	0.00028	0.001	0.0001	9/32
WC 25--	69.7-95.9	31.8-43.6	0.250	0.290	0.020	0.00025	0.001	0.0001	1/4
WC 22--	79.3-110	36.4-49.8	0.219	0.259	0.020	0.00025	0.001	0.0001	7/32
WC 19--	92.9-128	42.4-58.1	0.188	0.228	0.020	0.00025	0.001	0.00007	3/16
WC 17--	101-139	46.3-63.5	0.172	0.212	0.020	0.00025	0.001	0.00007	11/64
WC 14--	124-171	56.6-77.6	0.141	0.181	0.020	0.00025	0.001	0.00006	9/64
WC 13--	139-192	63.5-87.2	0.125	0.155	0.015	0.00025	0.001	0.00005	1/8
WC 11--	159-219	72.7-99.7	0.109	0.139	0.015	0.00025	0.001	0.00005	7/64
WC 9--	186-256	84.8-116	0.094	0.124	0.015	0.00025	0.001	0.00005	3/32

Note: Outside diameter, wall thickness, and wall thickness tolerance are omitted on WC 992 and larger sizes since it is anticipated that manufacturing methods will vary widely depending upon the individual application.

an equivalent frequency range, the attenuation constant is 61 to 73 percent of rectangular waveguide and the power handling capacity is about 110 percent that of rectangular waveguide. It is possible to propagate simultaneously two independent waves whose direction of polarization are orthogonal in a single circular guide. This property can be put to advantage in the operation of microwave communication relays because a single transmission line can be used to the receiver and transmitter antenna, and in certain components whose operation depends on directional polarization. The extent of mutual coupling between these two waves depends on the degree of ellipticity of the cross section, which must be carefully controlled. Bends and transitions are simpler to fabricate in circular guides operating in the TE_{11} mode than in the TE_{01} mode.

The TE_{01} circular mode has the unique property of an attenuation constant which decreases continuously with increasing frequency. For the same frequency region its mid-band attenuation is 13 to 16 percent of that of a rectangular guide (Fig. 8-29). The TE_{01} mode power-handling capacity is approximately 6 times greater than rectangular guide and circular guide in the TE_{11} mode (Table 8-26). For the same frequency coverage, the diameter of the circular waveguide in the TE_{11} mode must be kept to about half of that of the TE_{01} mode to eliminate the TE_{11} mode which is very difficult to suppress. Because of these advantages, operation in the TE_{01} mode becomes increasingly suitable, particularly for the millimeter region where size and dimensional tolerance become very critical. Since there is no current flow along the direction of the waveguide axis, connectors, rotary joints, and certain mode absorbers are extremely simple to make. However, any asymmetrical distortions or mechanical imperfections in the waveguide tubing create other modes which do not dampen

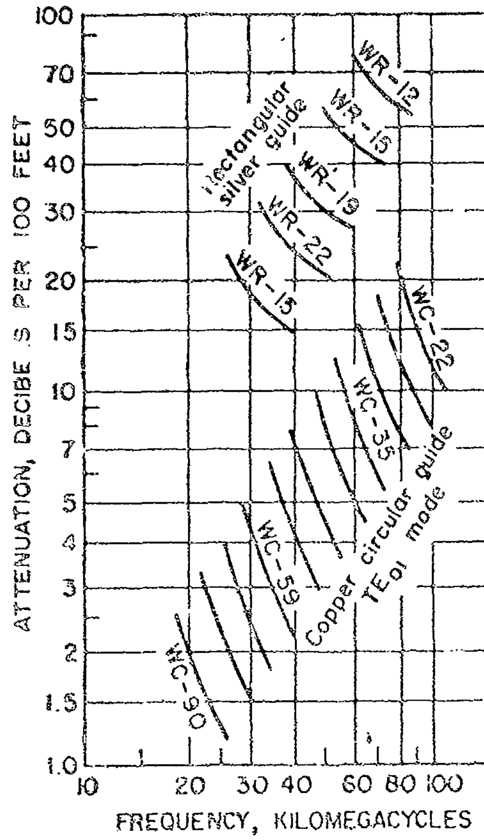


Fig. 8-29. Attenuation of rectangular and circular waveguides in the millimeter region.

out as quickly as in the rectangular guide. (Three lower order modes, TE_{11}, TM_{01}, and TE_{21}, are possible; the TM_{11} mode is degenerate with, or identical to, the TE_{01} mode.) Inadequate designs for close radius bends for any arbitrary angle still present a major deterrent to the use of the TE_{01} mode. (47,48) For very long lengths, however, multimode operation is practical because a large percentage of the energy in all the modes will eventually be coupled back to the TE_{01} mode. For example, an oversize copper guide can be used which affords dissipative losses of 2 db per mile under the range of conditions shown in Table 8-27. The higher frequency is more favorable with regard to increased transmission band width, reduced delay distortion and lower waveguide cost. (49)

Ridged Waveguides

Ridged waveguides achieve broad-band transmission by the addition of a symmetrical ridge from the center of the broad faces of a rectangular guide. Either a single or a double ridge may be used, with configurations as shown in Tables 8-28 and 8-29. The electrical performance of both types is very similar, but double-ridged waveguide is preferred for long transmission lines since the depth of ridge is roughly half that of a single ridge. This makes it simpler to hold tolerances on the ridge and to fabricate bends and flexible counterparts. The single-ridged waveguide is more practical for certain components and transitions to coaxial lines.

Band Width. The addition of the ridge lowers the cutoff frequency of the fundamental mode without having as large an effect on the higher modes. There is a wide range of theoretical band widths possible because of the almost unlimited number of geometric combinations available. The optimum ratio of ridge to waveguide width (s/a) varies between 0.15 and 0.25 for single ridge, and 0.25 to 0.30 for double ridge for band widths up to 5. (50) For this s/a ratio, the maximum gap height will result for the desired band width, and the resultant cross section will generally be a compromise between the lowest attenuation and greatest power handling capabilities. The lowered cutoff frequency also permits a more compact cross section and a lower wave impedance structure. (See Fig. 8-30.)

Single-Ridge Waveguide. Two types of ridged waveguides have been used and are being proposed for standardization. The first is of the single-ridge construction with an extremely broad operating frequency range of 4:1 whose characteristics are shown in Table 8-28. This increased band width is secured at the cost of increased attenuation which is 11.6 times as great as a rectangular waveguide with the same λ_c and aspect ratio. The corners of the ridge are rounded to a minimum radius of 0.1d (see Table 8-28) to prevent electric breakdown at the corners. The cw power capacity is about 2 percent that of rectangular waveguide because the breakdown will then occur in the narrow gap. The attenuation and power characteristics are fairly constant over the entire band except near the lower frequencies where λ_g tends to vary rapidly. Despite these limitations, such ridged waveguides and their associated components are advantageous in universal test equipment and for wide-band microwave receivers of the crystal video type.

When compared to a rigid air dielectric coaxial line of optimum impedance for minimum attenuation (93 ohms) and for maximum power capacity (44 ohms), the ridged wave-

Table 8-26—Comparison of CW Power Capab[illegible]ed Circular Waveguide

EIA type	TE_{11} mode		TE_{01} mode	
	Frequency range (kMc) (f_1 to f_2)	CW break-down (Mw) (f_1 to f_2)	Frequency range (kMc) (f_1 to f_2)	CW break-down (Mw) (f_1 to f_2)
WC 240	--	--	7.25-9.98	2.0-3.0
WC 128	--	--	13.6-18.7	0.61-0.89
WC 94	8.40-11.6	9.28-0.43	[illegible]-25.6	0.44-0.39
WC 59	13.4-18.4	0.12-0.19	29.3-40.4	0.15-0.23
WC 33	21.2-29.7	0.048-0.082	53.1-73.1	0.050-0.072
WC 28	28.3-38.0	0.028-0.048	--	--
WC 14	56.6-77.5	0.0082-0.013	--	--

Table 8-27—Characteristics of Multimode Circular Waveguide in TE_{01} Mode

Carrier frequency (Mc)	I.D. of tubing (in.)	Number of possible modes
5,500	6	20
50,000	2	175

guide exhibits better perfo[illegible]ance for theoretical band widths of abo[illegible] 4.0 and 3.0 respectively. Figures 8-31 and 8-32 illustrate such a theoretical comparison with a standard 50-ohm coaxial line.

Double-Ridge Waveguide. The second class is a proposed double-ridged waveguide with a moderate operating band width of about 2.4:1 whose characteristics are shown in Table 8-29. By reducing the band width, the attenuation and power capabilities are improved considerably and are more compatible with

Table 8-28—Extremely Broad Band Single-Ridge Waveguide

Frequency range (kMc)	Dimensions (in.)							Attenuation at $1.5f_c$ for aluminum (db/ft)	CW power-handling capability* (kw)
	a	b	d	s	t	r_1	r_2		
1.0-4.0	3.047	1.371	0.200	0.669	0.050	0.016	0.031	0.021	375
3.75-15.0	0.8125	0.3753	0.5315	0.1784	0.100	0.005	0.008	0.15	25
10.0-40.0	0.305	0.133	0.0215	0.073	0.060	0.005	0.008	3.55	3.8

* E_{max} = 15 kv/cm

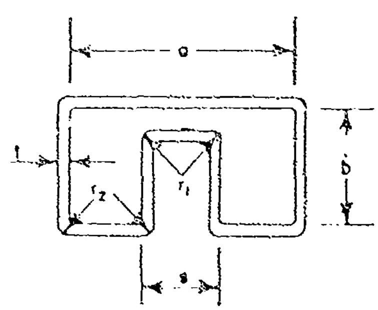
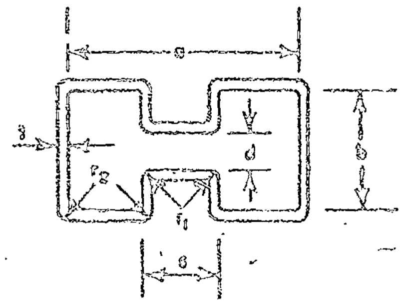


Table 8-29—Proposed Moderate Band-Width Double-Ridge Waveguide

Frequency range (kMc) Series A	Frequency range (kMc) Series B	Dimensions (in.) a	b	d	c	s	r_1	r_2 (max)	Calculated attenuation at $\sqrt{3} f_c$ (db/ft) Aluminum	Copper
0.96-2.20		5.000	2.500	1.000	1.500	0.125	0.125	0.045	0.0045	—
	1.45-3.33	3.400	1.700	0.680	0.850	0.125	0.125	0.045	0.003	—
2.15-4.95		2.310	1.155	0.519	0.577	0.080	0.080	0.045	0.0135	—
	3.00-6.90	1.660	0.830	0.374	0.415	0.080	0.080	0.030	0.022	—
4.70-11.0		1.025	0.475	0.191	0.256	0.050	0.060	0.030	0.055	—
	6.50-15.0	0.760	0.380	0.1[illegible]	0.190	0.050	0.050	0.030	0.069	—
9.60-22.0		0.500	0.250	0.100	0.125	0.040	0.025	0.015	0.140	0.114
	14.5-33.0	0.340	0.170	0.077	0.085	0.040	0.015	0.015	0.24	0.19
21.5-41.5		0.240	0.120	0.057	0.060	0.040	0.010	0.010	0.37	0.29
	30.0-69.0	0.166	0.083	0.038	0.042	0.040	0.008	0.007	—	0.54
47.0-110		0.104	0.052	0.022	0.026	0.040	0.005	0.006	—	1.15
	65.0-150	0.80	0.040	0.020	0.020	0.025	0.005	0.005	—	1.50
Special aeronautical radio type										
5.20-9.60		1.222	0.651	0.403	0.351	0.064	0.060	0.030	(See Table 8-30)	



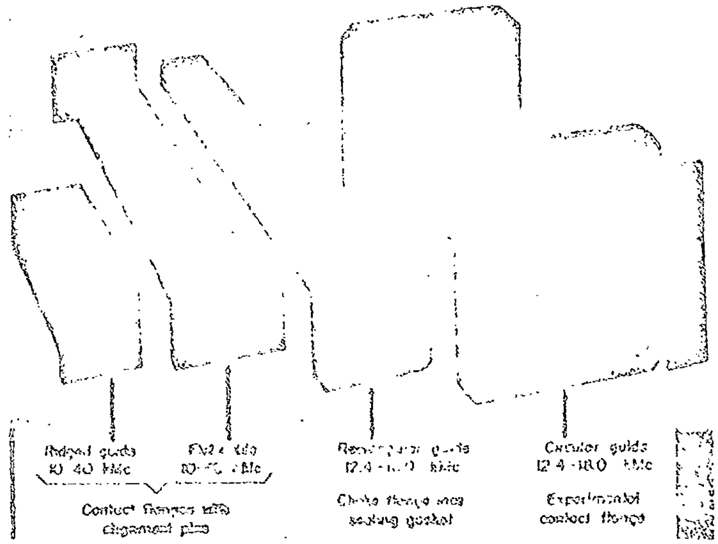


Fig. 8-30. Comparison of typical transmission lines and end flanges.

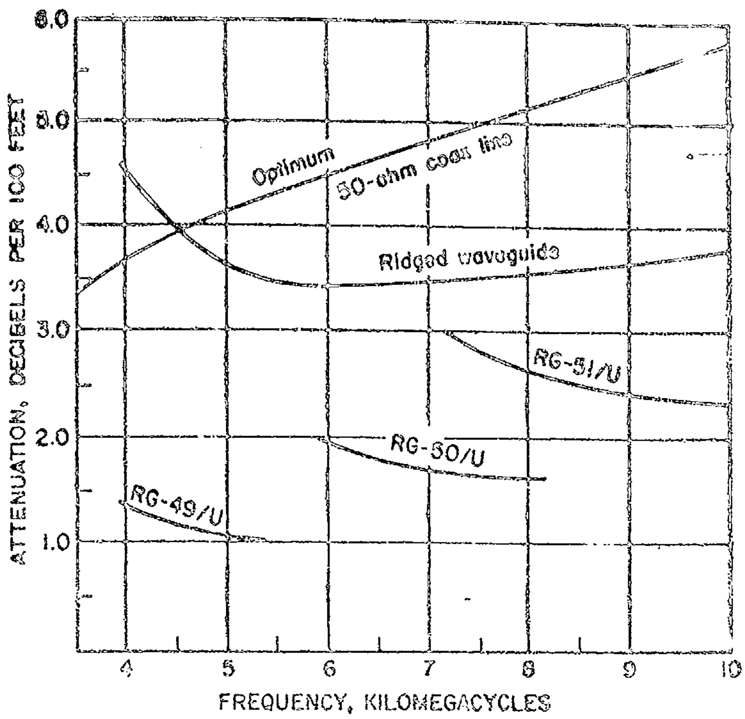


Fig. 8-31. Attenuation of ridged waveguide, optimum 50-ohm coaxial line, and rectangular waveguides.

current broad-band oscillators and amplifiers. Little data are available on these types because design criteria and final dimensions have not been established nor have any of these exact ridged waveguides been manufactured in quantity to date. However, a very similar double-ridged waveguide has been adopted by Aeronautical Radio, Inc., for commerical weather penetration radar to permit operations at either the 5400 or 9300 Mc band. (51) Constructional details of this waveguide are also included in Table 8-29 and measured characteristics are shown in Table 8-30. These initial values are roughly 2-1/2 times theoretical for 2-S aluminum which has been attributed to higher surface roughness around the ridge than would normally be expected.

In general, materials, finishes, construction techniques, tolerances, and soon, are basically the same for ridged waveguides as for the rectangular waveguides previously discussed. Tolerance on the gap distance (d) is particularly critical. The connectors used are of the contact type only, but otherwise are very similar to those for the rectangular waveguide. Flexible ridged waveguides are also available in certain sizes with moderate ridge protrusions.

Flexible Waveguides

Flexible waveguides are used to supplement rigid rectangular or circular waveguides at certain strategic points in a transmission line system. They are used to: (1) connect sections which would require complex bends and twists, (2) provide expansion and contraction joints in long lines, (3) reduce the transmitted shock and vibration to sensitive devices such as magnetrons, (4) connect antennas that nod, tilt, or rotate less than a complete revolution, and (5) provide flexible leads for test equipment or (6) overcome difficult installation problems. They are seldom required in long lengths and are customarily procured in finished assemblies with attached flanges. Special flanges and attachment techniques are required for each type of flexible waveguide, together with molded rubber jackets which normally cannot be applied by the user. A general performance specification, MIL-W-287, "Waveguide Assemblies, Flexible," is available, but it does not encompass detailed requirements for the great majority of types currently in use.

Construction. Flexible waveguides may be classed as either resonant or nonresonant

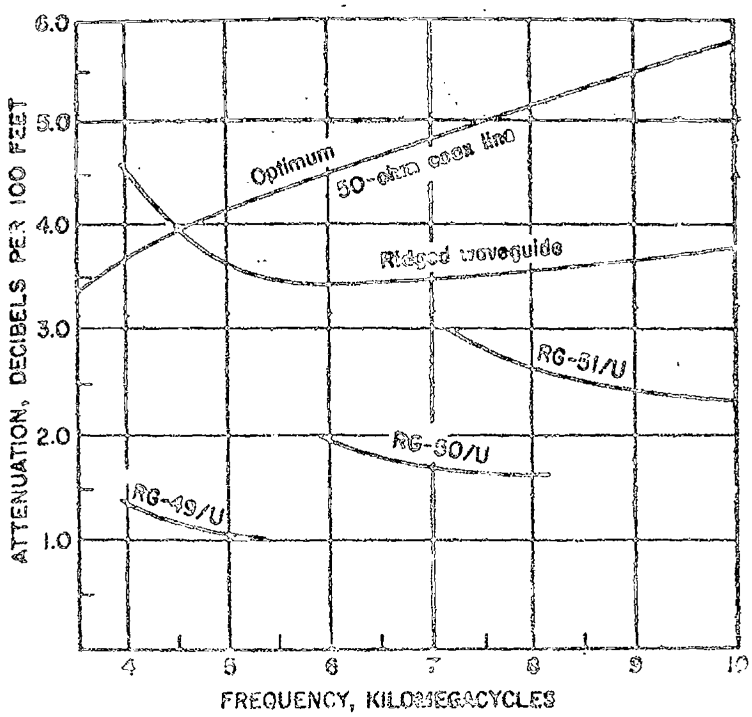


Fig. 8-31. Attenuation of ridged waveguide, optimum 50-ohm coaxial line, and rectangular waveguides.

current broad-band oscillators and amplifiers. Little data are available on these types because design criteria and final dimensions have not been established nor have any of these exact ridged waveguides been manufactured in quantity to date. However, a very similar double-ridged waveguide has been adopted by Aeronautical Radio, Inc., for commercial weather penetration radar to permit operations at either the 5400 or 9300 Mc band. (51) Constructional details of this waveguide are also included in Table 8-29 and measured characteristics are shown in Table 8-30. These initial values are roughly 2-1/2 times theoretical for 2-S aluminum which has been attributed to higher surface roughness around the ridge than would normally be expected.

In general, materials, finishes, construction techniques, tolerances, and so on, are basically the same for ridged waveguides as for the rectangular waveguides previously discussed. Tolerance on the gap distance (d) is particularly critical. The connectors used are of the contact type only, but otherwise are very similar to those for the rectangular waveguide. Flexible ridged waveguides are also available in certain sizes with moderate ridge protrusions.

Flexible Waveguides

Flexible waveguides are used to supplement rigid rectangular or circular waveguides at certain strategic points in a transmission line system. They are used to: (1) connect sections which would require complex bends and twists, (2) provide expansion and contraction joints in long lines, (3) reduce the transmitted shock and vibration to sensitive devices such as magnetrons, (4) connect antennas that nod, tilt, or rotate less than a complete revolution, and (5) provide flexible leads for test equipment or (6) overcome difficult installation problems. They are seldom required in long lengths and are customarily procured in finished assemblies with attached flanges. Special flanges and attachment techniques are required for each type of flexible waveguide, together with molded rubber jackets which normally cannot be applied by the user. A general performance specification, MIL-W-287, "Waveguide Assemblies, Flexible," is available, but it does not encompass detailed requirements for the great majority of types currently in use.

Construction. Flexible waveguides may be classed as either resonant or nonresonant

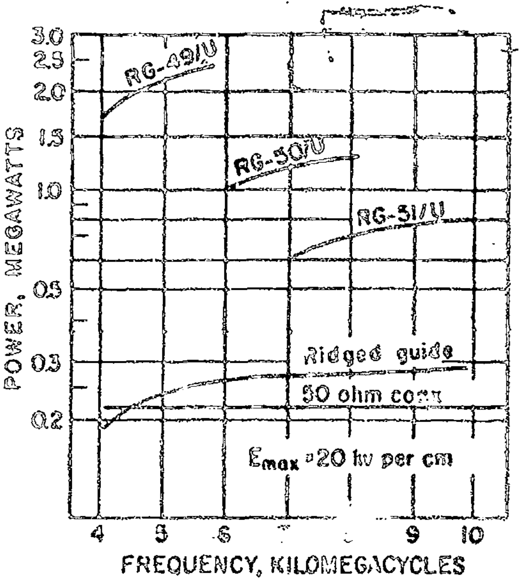


Fig. 8-32. Power handling capacity of ridged waveguide, 50-ohm coaxial line, and rectangular waveguide.

types. The nonresonant types are fabricated from spiral wraps (interlocked, soldered convolute, unsoldered convolute) or from thin-wall tubing (seamless corrugated or null-point seam). The resonant types consist of the bellows or vertebra construction. The significant features of each of these constructions are indicated below and shown in the cutaway sections of Fig. 8-33.

1. Interlocked. This waveguide is made by spirally winding a thin, formed, silver-coated bronze strip about an arbor, folding in and interlocking the edges tightly to produce a flexible rectangular tubing which has good electrical contact between convolutions. This type of waveguide flexes by virtue of a sliding motion which takes place between convolutions as it is stretched, compressed, bent, or twisted. The formed waveguide is cut to proper lengths and connectors are soldered on. A rubber jacket, molded over the surface of the entire assembly, provides pressurization features, offers considerable protection to the metal tubing, and increases the assembly life for repeated flexings. For special applications a nonjacketed version of this waveguide can be used. This type is particularly useful in lengths from about 6 inches to 4 feet. It is relatively frequency insensitive and has a VSWR below 1.05 over the entire frequency band. It has an attenuation about twice that of rigid-silver tubing.

Table 8-30—Measured Electrical Performance of Special Double-ridged Waveguide

Peak power (2.5 microsecond pulse at 400 pulses/second)	1,000 kw at 5400 Mc 1,280 kw at 9375 Mc
Attenuation, db/ft	0.047 at 5400 Mc 0.[illegible]13 at 9375 Mc

2. Soldered convoluted. This waveguide is constructed by winding a very thin metal strip spirally on a rectangular form. Adjacent turns are crimped a small amount and the crimped edges are soft soldered. When this waveguide is flexed there is no sliding of adjacent turns, but a flexing of each individual turn. After winding, the tubing is cut to the required length, connectors are fastened and a rubber jacket molded around it. This waveguide is more flexible than the interlocked waveguide and can be compressed and extended to a greater degree. However, it is more fragile and cannot be twisted to any degree.

3. Unsoldered convoluted. This type of construction is similar to the soldered convoluted type except that the crimped edges are not soldered. This waveguide cannot be bent as sharply as the soldered variety, but can be twisted. The electrical characteristics are similar to the interlocked and soldered convoluted types.

4. Seamless corrugated. This type is constructed by convoluting thin-wall, seamless, rectangular metal tubing. It is fabricated from soft annealed copper for use as shock absorbing couplings to fragile components, to magnetrons, for example. It is also made from bronze tubing when a "springy" variety is desired. It can be obtained with or without a rubber jacket. This type will stretch, compress, and bend more than interlocked or convoluted types but cannot stand any twisting. The electrical properties are good. It is usually supplied in short sections only. A variation of this type is manufactured in the RG-48 and 52/U waveguide sizes. It is formed from two U-shaped halves of silverplated beryllium copper, soldered along the midpoint of the narrow walls. It can withstand relatively sharp bends but negligible twist and extension or compression. Its life under repeated flexing can be greatly improved by annealing the beryllium copper in the desired direction of bend, prior to molding of the rubber jacket.

5. Null-point seam or axial seam. This type is constructed of a corrugated sheet folded to form a rectangular tube with annular cavities or bellows. The lap seam is located

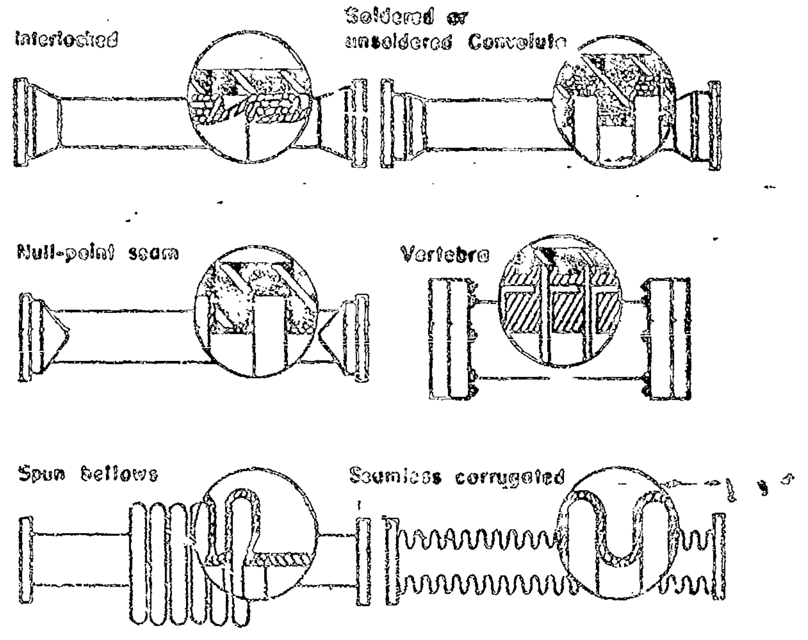


Fig. 8-33. Flexible waveguide constructions.

in the center of the larger cross-sectional dimension and is offset to provide a smooth inside contour. The tubing is either bimetallic (silver inner face brazed or welded on a high fatigue resistance alloy base) or silver-plated bronze. The electrical properties are as good as any of the other flexible waveguides. It is available in all lengths and can be obtained with or without a rubber jacket.

6. Vertebra. This type consists of a number of open choke-cover joints* held in alignment and properly spaced by a rubber jacket. Adjacent junctions are spaced approximately 1/4 wavelength apart and generally an even number of such junctions is employed, which makes possible the cancellation of reflections from all junctions, thereby keeping the overall VSWR small. For pressurized applications, the rubber jacket is covered with a metal armor. The armor reduces the flexibility but acts as an r-f shield. This waveguide is used in short sections (up to 12 inches) as it is bulky and heavy. It can be extended, compressed, bent in both E and H planes, sheared in either plane, or twisted axially at low rates of speed. The static electrical characteristics are maintained under most conditions of mechanical deformation. This waveguide has more degrees of mechanical freedom than any existing waveguide.

7. Bellows. The flexible sections consist of radial chokes made of a flexible alloy forming a bellows. Between radial chokes there is a partition containing a rectangular hole having the dimensions of the inside of the waveguide. Any number of these sections can be stacked together to make a flexible waveguide. This type is quite flexible but cannot be twisted. Resonances, which cause large mismatches, exist for some critical frequencies when the waveguide is bent or stretched from its normal position.

Electrical Characteristics. The internal dimensions of the nonresonant types of flexible waveguides approximate those of the rigid waveguide with which they are intended to mate. Although some adjustments must be made for the irregular contours, the generous corner radii required, and the wall convolutions, a good impedance match with rigid waveguides can generally be achieved. Some reflections are introduced at the couplings, but the VSWR of a relaxed complete assembly can generally be kept below 1.05 over the entire waveguide band width. The VSWR will increase somewhat as the extremes of twisting, shearing, bending, or extension of the flexible elements are approached. As would be expected, the attenuation is considerably higher than that of the rigid waveguide because the corrugations increase the longitudinal conductivity path by two or three times. The power capability of flexible waveguide is at

*Choke-cover joints will be discussed further under waveguide couplings.

least equal to, and in some cases exceeds, that of rigid waveguide although data are very limited. Typical characteristics on the soldered convolute type are shown in Table 8-31, and comparable data on other types are contained in Reference 52.

Resonant types are much more restricted with regard to band width and power capability. The vertebra type is the most versatile mechanically, and has been used widely in medium and small sizes (RG-48 through 53/U). Band-width limitations have been overcome on more recent designs. (53) A VSWR of 1.10 or less is possible over a 40-percent frequency band for the vertebra waveguide in the relaxed position. Some typical values of displacement which can be tolerated without significant increase of the VSWR are:

Equivalent waveguide size	Extension (in.)	E or H plane shear (in.)	Angular rotation (deg)
RG-48/U	0.600	0.600	21
RG-49/U	0.411	0.411	23
RG-52/U	0.200	0.200	33

The bellows types have been used primarily for narrow-band operation (6 percent) and their power level is limited by the breakdown which occurs across the rectangular openings between the sections. They are difficult to manufacture, are used in short sections, and generally are limited to internal applications.

There is no universally applicable flexible waveguide but certain constructions are more suitable for specific types of loading as shown in Table 8-32. However, the properties of flexible waveguides vary widely according to the metal employed, its thickness and temper, as well as with the composition and contour of the protective jacket. In critical applications the manufacturers should be consulted for their recommendations.

Unjacketed flexible waveguides should not be used in locations where sustained exposure to moisture, salt spray, or similar atmospheric contaminants will corrode the metallic joints. Neoprene or natural rubber jackets serve to protect the seams and improve their overall flexibility. The jacket compound must

Table 8-31 — Properties of Soldered Convolute Flexible Waveguides

Dimensions (in.)		Minimum bending radii (in.)		Equivalent rectangular waveguide	Weight (lb/ft)	Nominal attenuation (db/100 ft)	Nominal power rating (Mw)	Maximum operating pressure (psi)
		Standard molded assembly	Unjacketed or special molded assembly					
Inside	Outside	H plane E plane	H plane E plane					
6.500 × 3.250	6.660 × 3.410	27 13	17 8-1/2	RG-69/U	2.80	0.80	10	15
4.300 × 2.150	4.460 × 2.310	18 9	11-1/2 5-3/4	RG-104/U	1.40	0.09	6.0	30
2.840 × 1.340	3.000 × 1.500	14 7	9 4-1/2	RG-48/U	0.530	1.5	2.0	20
1.872 × 0.872	2.000 × 1.000	8 4	5 2-1/2	RG-49/U	0.332	3.0	1.0	20
1.372 × 0.622	1.500 0.750	5 2-1/2	3-1/4 1-5/8	RG-50/U	0.266	4.7	0.50	30
1.122 × 0.497	1.250 × 0.625	3-1/2 1-3/4	2-1/4 1-1/8	RG-51/U	0.230	5.7	0.[illegible]	45
0.900 × 0.400	1.000 × 0.500	3 1-1/2	2 1	RG-52/U	0.112	9.0	0.35	60
0.622 × 0.311	0.702 × 0.391	3 1-1/2	2 1	RG-91/U	0.065	15.0	0.20	60
0.420 × 0.170	0.500 × 0.250	2-1/2 1-1/4	1-1/2 3/4	RG-53/U	0.050	20.0	0.10	60
0.280 × 0.140	0.360 × 0.220	2-1/2 1-1/4	1-1/2 3/4	RG-96/U	0.039	35.0	0.05	60

Table 8-32—Mechanical Properties of Flexible Waveguides

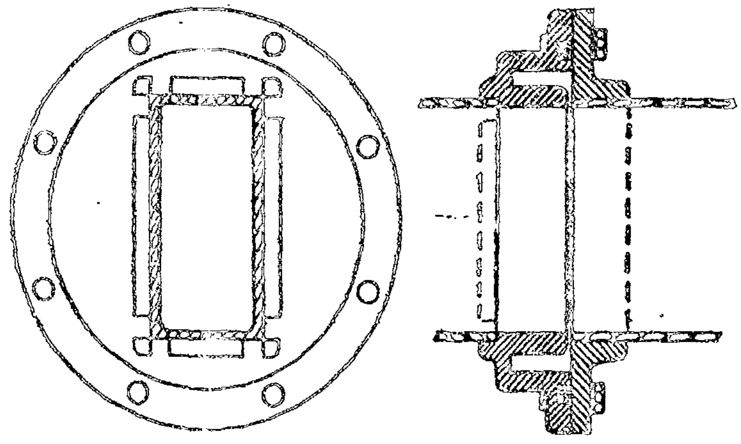
Type of flexible waveguide	Bend		Twist		Longitudinal	
	Relatively sharp	Moderately sharp	Appreciable	Negligible	Relatively large	Relatively small
<u>Nonresonant types</u>	Static deformation					
Interlocked		x	x			x
Unsoldered convolute	x		x			x
Soldered convolute	x			x		x
Null-point seam	x			x		x
Seamless corrugated	x			x	x	
<u>Resonant types</u>						
Vertebra		x	x		x	
Bellows		x			x	
<u>Nonresonant types</u>	Repeated deformation					
Interlocked		x	x			x
Unsoldered convolute	x		x			x
Soldered convolute		x		x		x
Null-point seam		x		x		x
Seamless corrugated		x		x		x
<u>Resonant types</u>						
Vertebra	x		x		x	
Bellows	x				x	

resist embrittlement and eventual cracking under the deleterious ageing effects of sunlight and elevated temperatures.

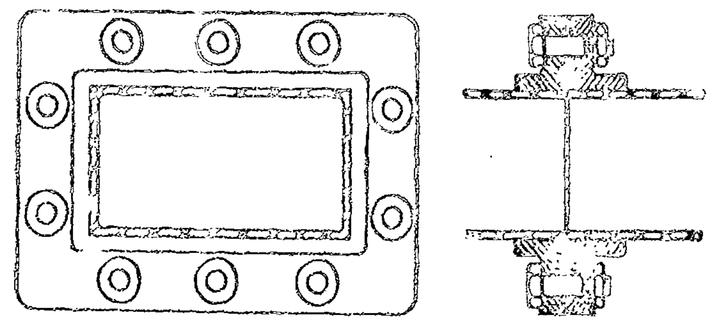
Waveguide Couplings

Waveguide couplings can be grouped into two general classes: contact couplings and choke couplings. A contact coupling consists of two flanges, each soldered, welded, or brazed to the end of the waveguide, and bolted together as shown in Fig. 8-34. The waveguide tubing generally extends through the flange and is machined flush with it after assembly. The flange faces must be clean, free from corrosion, and accurately machined to assure intimate contact around the inner periphery of the waveguide opening when the coupling is assembled. Reflections from a new, well-made coupling can be kept below a VSWR of 1.01. However, this performance deteriorates rapidly in the presence of any corrosion product or mechanical irregularities on the mating faces as would normally be encountered in military usage. A thin spring-finger metal gasket was devised to fit between the flanges and assure contact at the inside periphery. A reduction and uniformity of VSWR is achieved as shown in Fig. 8-35, but the coupling is not pressurizable and is limited to internal use. Effective operation of the spring fingers depends upon very good alignment of the fingers and present trends are away from their use.

<u>Flanges</u>. The outside shape of a contact flange varies with waveguide size. In the very small sizes, from RG-97 to 99/U, a circular flange is used with four special captive screws and two pins for alignment purposes. Square flanges with drilled holes at the four corners are used from the RG-51/U



TYPICAL CHOKE COUPLING



TYPICAL CONTACT COUPLING

Fig. 8-34. Waveguide couplings.

to and including the RG-96/U sizes, which also serve as cover flanges in a choke coupling. For larger sizes the contact flanges are rectangular, with provisions for sealing gaskets. A new series of precision miniature unpressurized contact flanges in the size range of WR90 (RG-52/U) to WR284 (RG-48/U) has been recently established under EIA Standard RS-166. These are intended for internal equipment interconnections where mechanical stresses on the couplings are light. The VSWR of a coupling can be kept as low as 1.003 by the use of special drilling jigs after the flange blank has been assembled to the waveguide.

Choke Coupling. The choke coupling is relatively simple to assemble as it is not necessary for the flange faces to make contact at the waveguide ends (Fig. 8-34). At the junction a series branching half-wave transmission line is introduced. It presents a zero impedance to the main line. The outer quarter-wavelength section is usually in the form of a complete circular groove for simplicity of manufacture. The VSWR of a broadband choke coupling can be kept to 1.02 over the frequency range of the guide. The VSWR is unaffected by surface condition and moderate misalignment in the E plane or H plane, although angular misalignment should be avoided. For example, a linear misalignment of 0.020 inch can be tolerated in either direction for the RG-52/U (1 by 1/2 inch) waveguide. Resonances, sharp corners, or foreign particles in the choke groove, will introduce high local voltage stresses sufficient to cause breakdown. This difficulty is particularly troublesome in the presence of any higher harmonics, that is, for the second

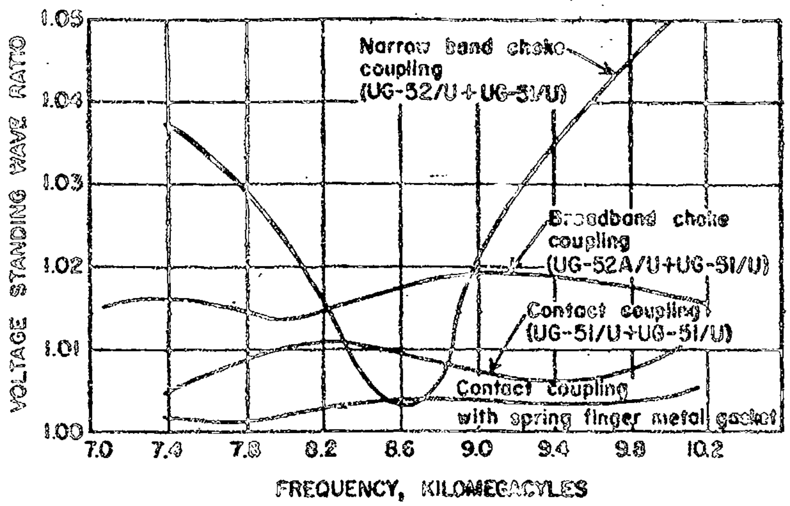


Fig. 8-35. VSWR for various waveguide couplings for RG-51/U waveguide.

harmonic, 8 possible modes can exist; and for the third harmonic, 23 modes are possible in the waveguide. The choke section can resonate with one or more of these modes, or the phase of several of these standing waves can be additive to produce a high local field strength. For high power application, the section of the choke groove which subtends the narrow face of the rectangular guide should be omitted or filled (slugged) to reduce higher mode excitation.

Choke couplings are practical over the waveguide size range from RG-48 to 91/U. Square flanges are preferred in the smaller sizes, and circular flanges in the larger sizes to conserve space and weight. Choke flanges are not practical for the small waveguides used in the millimeter region due to the extreme dimensional tolerances required in the choke section and for the proper alignment of flanges. All choke flanges contain an O-ring gasket groove to provide a waterproof and pressurizable seal when mated with a cover flange.* Most of the standard sections such as bends, corners, twists, and motional joints are provided with a choke flange on one end and a cover flange on the other.

Requirements for military flanges are contained in Specification MIL-F-3922 "Flanges and Associated Fittings for Rectangular Waveguide Couplings," and detailed on the Military Standards (MS) sheets subsidiary thereto. Table 8-33 gives a listing of the preferred flanges recommended for military usage.

Specifications

Table 8-34 gives a brief summary of the contents of several of the military specifications covering waveguides, flanges, couplings, and other fittings.

EFFECTS OF ENVIRONMENT ON TRANSMISSION LINES AND WAVEGUIDES

The effects of environment on r-f lines and waveguides, as in all components, are directly related to the materials used in their construction. These items employ comparatively few types of materials, and they have been made the subject of careful study and improvement. The information that follows attempts to point out some of the overall causes of deterioration of performance, and suggested remedies where possible.

Temperature

Temperature effects fall into two categories: changes in performance and long-time deterioration. The most apparent change will be the variation in attenuation values as the resistivity of the conductors increases or decreases proportionally with temperature. The temperature coefficient of resistivity varies with each material, being approximately 0.4 percent per degree C for copper. The per-

* A cover flange is a contact flange which is designed specifically to mate with a choke flange. Two cover flanges will provide an unpressurized contact coupling, but not necessarily of the minimum size or optimum performance.

Table 8-33.—Preferred Waveguide Flanges

Type	Flange type	Material	For use with waveguide type	Military std. No.	Type of coupling
UG-417A/U* UG-418A/U*	Contact (+gasket) Contact (+gasket)	Copper alloy Aluminum	RG-69/U RG-103/U	MS90052	Contact Contact
UG-435A/U* UG-437A/U*	Contact (+gasket) Contact (+gasket)	Copper alloy Aluminum	RG-104/U RG-105/U	MS90053	Contact Contact
UG-553/U* UG-554/U*	Contact (+gasket) Contact (+gasket)	Copper alloy Aluminum	RG-112/U RG-113/U	MS90051	Contact Contact
UG-53/U UG-54A/U	Cover Choke (+gasket)	Copper alloy	RG-48/U	MS90045 MS90044	Choke
UG-584/U UG-585/U	Cover Choke (+gasket)	Aluminum	RG-75/U	MS90043 MS90044	Choke
UG-149A/U UG-148B/U	Cover Choke (+gasket)	Copper alloy	RG-49/U	MS90047 MS90046	Choke
UG-407/U UG-406A/U	Cover Choke (+gasket)	Aluminum	RG-95/U	MS90047 MS90046	Choke
UG-344/U UG-343A/U	Cover Choke (+gasket)	Copper alloy	RG-50/U	MS90049 MS90048	Choke
UG-441/U UG-440A/U	Cover Choke (+gasket)	Aluminum	RG-106/U	MS90049 MS90048	Choke
UG-51/U UG-52A/U	Cover Choke (+gasket)	Copper alloy	RG-51/U	MS90061 MS90060	Choke
UG-138/U UG-137A/U	Cover Choke (+gasket)	Aluminum	RG-68/U	MS90061 MS90060	Choke
UG-39/U UG-40A/U	Cover Choke (+gasket)	Copper alloy	RG-52/U	MS90059 MS90058	Choke
UG-135/U UG-136A/U	Cover Choke (+gasket)	Aluminum	RG-67/U	MS90059 MS90058	Choke
UG-419/U UG-541/U	Cover Choke (+gasket)	Copper alloy†	RG-91,107/U	MS90063 MS90062	Choke
UG-595/U UG-596/U	Cover Choke (+gasket)	Copper alloy†	RG-53, 66/U	MS90056 MS90054	Choke
UG-597/U UG-598/U	Cover Choke (+gasket)	Aluminum	RG-121/U	MS90056 MS90054	Choke
UG-599/U UG-600/U	Cover Choke (+gasket)	Copper alloy†	RG-96/U	MS90057 MS90055	Choke
UG-383/U* UG-385/U* UG-387/U*	Contact (+gasket) Contact (+gasket) Contact (+gasket)	Copper alloy†	RG-97/U RG-98/U RG-99/U	MS90050	Contact Contact Contact

* Two identical flanges must be used for a contact junction. In a pressurized junction, one surplus gasket is used as a spare.

† Flanges are silver-plated after assembly when used with silver waveguides.

mittivity and dissipation factor of the dielectric material are comparatively constant over its useful temperature range. Hence, the electrical parameters of the line, other than attenuation, are virtually independent of temperature fluctuations for short periods of time.

Much more troublesome are the effects of repeated cycling over wide temperature ex-

Table 8-34—Waveguides and Fittings

Number and title	Scope
MIL-W-85C, "Tubing, Waveguide Seamless, Rectangular."	General specification for all sizes of rectangular waveguides and materials used therein.
MIL-W-287, "Waveguide Assemblies Flexible, General Specification."	Establishes general test procedures and incorporates detail requirements for one size and type of waveguide.
MIL-F-3922 "Flanges and Associated Fittings for Rectangular Waveguide Couplings."	General specification for all types of flanges except for the miniature unpressurized type.
MIL-W-18908(Ships), "Waveguides RG-184/U."	Establishes requirements for a thin-wall version of the RG-69 waveguide.

tremes, due to the large difference in thermal expansion rates between the metals and the thermoplastic materials, particularly for solid dielectric cables. At elevated temperatures the dielectric is restrained radially, and undergoes an irreversible cold flow in the axial direction. Any residual process strains also tend to be relieved at the higher temperature, contributing to dimensional changes. When the temperature is subsequently reduced, a loose mechanical fit can occur and markedly reduce the corona limit, and change the characteristic impedance slightly. This effect is even more pronounced in a cable as the fine braid wires can be expanded beyond their elastic limit. If the outer coverings, such as a glass fiber or steel braid, exert greater constraint, the longitudinal expansion may be sufficient in short lengths of Teflon and long lengths of polyethylene dielectric cables to cause connectors to malfunction or even become dislodged. Recommended upper temperature limits for solid dielectric cables should be carefully observed to minimize such plastic flow which is greatly increased near the softening point. In long runs of rigid coaxial lines or waveguides, provision should be made for a sliding or flexible section to compensate for longitudinal expansion and contraction.

Natural chemical changes are also greatly accelerated when the materials are maintained at an elevated temperature. Metallic surfaces combine more readily at high temperatures with atmospheric gases and volatiles given off from the surrounding organic materials (for example, sulphur from rubber or chlorine from polyvinyl chloride). Silver platings on wire have been found to go into solid solution with copper after sustained exposure at 200 C. Conductors and spring contact members progressively lose their tensile strength, ductility, and flexibility. A similar embrittlement will also occur with all the elastomer and plastic jacketing materials. This will become evident by a rapid loss of pliability at sub-zero temperatures, and ultimate shattering or cracking.

Due to natural oxidation the dissipation factor of most dielectrics increases with time at a rate that is temperature dependent. In addition, polyethylene has a chemical affinity for some of the volatile plasticizers used in vinyl jackets, which causes very large changes in dissipation factor. Special "noncontaminating" vinyl jackets must be used to maintain attenuation stability over long periods of time. Teflon is not affected by such aging.

Pressure and Humidity

Variations in pressure and humidity will affect permissible voltage and power ratings of transmission lines. The mechanisms controlling electric breakdown depend upon gas density which varies directly with the pressure and inversely as the absolute temperature. Curves are available which relate pressure and temperature to altitude and permit correction of the maximum electric field strength. The corona level of solid dielectric cables requires the same correction data for sustained periods of high altitude operation. Gaseous diffusion takes place through the jacket and the dielectric so as to eventually equalize the internal pressure with that of the surrounding atmosphere. To overcome these

limitations, and to minimize corrosion, some nominal pressurization is employed in almost all waveguides and rigid or semiflexible air articulated coaxial lines. For high-power applications the internal pressure is increased to two or three atmospheres without any undue stiffening or rupture of the flexible waveguide.

The density of the surrounding air also determines the ability of the line or cable to dissipate heat from the outer surface by convection. At sea level, convection accounts for virtually all the heat dissipated, and hence determines the thermal power rating. Such ratings must be severely reduced, due to the rarified atmosphere encountered at high altitudes, unless provision can be made for removal of heat by radiation or conduction. For example, for Teflon cables the ratio of the power at sea level to that at any other altitude is equal to the ratio of the pressures raised to the 0.26 power.

Relative humidity is of little concern since most transmission line systems are sealed and the dielectric materials commonly used are nonhygroscopic. Certain elements of the system (for example, antenna feeds and sealing windows) will at times be subjected to a combination of high humidity and temperature sufficient to cause condensation of moisture on the exposed surfaces and possible arc over. Arc-resistant materials which do not carbonize, for example Teflon, glass, or glazed ceramics, should be used for these applications.

Atmospheric Contaminants

Precautions are required in the installation and in proper selection of finishes for exposed metallic lines and fittings to extend their useful life. Direct soil burial or locations where surface water cannot drain off freely should be avoided. Vertical runs of unsealed tubing should provide a "weep" hole at the lowest point in the line for the drainage of any accumulated moisture. Choke flanges can be particularly troublesome as water can accumulate in the recesses of the choke groove. The junctions of cable assemblies should be protected by a conformal wrapping of pressure-sensitive vinyl or self-sealing rubber tape where the connectors are to be installed underground or in any exposed location where there is no need for frequent uncoupling.

Metals are susceptible to electrolytic corrosion as a result of salt spray, or chemical fumes such as sulphur, hydrogen sulphide, or carbon monoxide, which form electrolytes in the presence of moisture. The copper and silver alloy materials are least affected and aluminum and magnesium alloys are most affected by corrosion of this type. Precious metal or oxide coatings used in the interior surfaces must have good electrical conductivity. However, the former are too costly and the latter are mechanically inadequate for external use without additional protection. An appropriate two-coat paint system should be used in accordance with the procedures of MIL-F-14072, "Finishes for Ground Signal Equipment."* Direct contact of dissimilar metals widely displaced in the galvanic series, such as the mating of aluminum and brass flanges, must be avoided. Where there is no alternative, both surfaces must be given a final plating of the same material; or a separator of an inert material must be used to prevent electromechanical action.

Cable jacket materials are quite resistant to all forms of atmospheric corrosion and fungi attack encountered in external locations. They are capable of one to three years of direct soil burial with only slight attack by the micro-organisms in the soil. However, these materials may suffer deleterious effects from the oils, gasolines, solvents, or hydraulic fluids normally encountered in aircraft, vehicular, or ground installations in which they are used. The vinyl materials are most resistant to these chemicals while the rubber materials, with the exception of neoprene, will all swell and soften on prolonged exposure. Silicone rubber is particularly poor in the presence of gasoline. Kel-F is the only material resistant to the effect of fuming nitric acid.

Mechanical Factors

Rigid lines and cables are quite rugged, and can withstand normal field handling with a few simple precautions. Long vertical runs should be supported periodically to remove the full stress from the couplings, particularly for cable connectors with spring loaded coupling rings. Static compression will cause a semipermanent deformation (that is, cold flow) of the thermoplastic dielectric and jacket materials. This constriction of the cross section causes a loss of sealing and introduces an additional VSWR at the connector junction. For air spaced cables, an auxiliary dielectric support should be used to support the conductor at the connector.

* NAVSHIPS 900-171, Chapter 11, contains the painting procedures employed by the Navy.

The radii of curvature should be kept as large as possible during installation, as sharp bends in cables introduce mechanical stress on the jacket and, to a lesser degree, on the dielectric. These stresses greatly accelerate the cracking of the jacket in the presence of ultraviolet rays in sunlight, and atmospheric ozone which is greatly increased in the presence of corona. The center conductor tends to migrate outward and has been known to short circuit to the braid under extremes of temperature cycling. Thick sections of low molecular weight polyethylene also rupture in contact with certain common soaps, greases, alcohols, and solvents when subjected to a biaxial stress. All these chemical reactions increase rapidly with temperature. Wherever possible, right-angle fittings should be used to eliminate sharp bends.

Coaxial cables have been designed primarily to permit reeling and unreeling rather than for any continuous flexure of twisting. If a limited degree of flexure is necessary, the cable should be installed so that the radius of bend changes in one direction only, rather than undergoing a reversal. All cables stiffen at low temperatures; the plastic materials much more rapidly than the elastomeric materials. Cables stored at sub-zero temperatures should be warmed prior to bending, because the forces involved become very high and can cause cracking of the jacket. Under continuous flexure or twisting, the braid will loosen and reduce the corona levels, and also cause erratic attenuation at the higher frequencies. In moderate twisting, the braids will usually fail first after about 10,000 cycles due to the high degree of abrasion they receive in the comparatively stiffer plastic cables. For predominant flexure, the center conductor will break first. Where extreme flexibility is desired, special constructions of the inner conductor and braid must be used as well as very elastic dielectrics.

Solid sheath cable should be fastened in a manner so as to minimize any vibration. All the ductile materials will work harder and eventually crack due to cyclic stress.

Nuclear Radiation

The type and intensity of nuclear radiation will vary greatly with the nature of the source, the distance from the source, and the duration of the exposure. The effects which take place immediately, such as in an explosion, are a function of the radiation flux or "dose rate." Degenerative effects associated with the total integrated dose absorbed (that is, the product of the dose rate and the time duration at that rate) are considerably different. The extent of damage sustained by any particular component will depend on its chemical composition, the total dosage, and a dose rate.

Quantitative data secured during an atomic blast are very limited and of a highly classified nature. However, extensive evaluation has been undertaken of the effect of radiation on materials required for electronic instrumentation and control of nuclear reactors. The correlation of such data on materials into quantitative performance is lacking, but a brief discussion of the behavior of the materials in common use is considered timely.

In close proximity to a reactor core, extremely high intensities of fast neutron and gamma radiations are emitted over a wide energy spectrum. The primary shield around the reactor will convert the fast neutrons to slow or thermal neutrons and reduce their intensity by a factor of 10^3 to 10^5, while gamma radiation is reduced by a factor of 10^3 to 10^4. Beyond the secondary shield, radiation effects are negligible.

Metals or their alloys are least affected, and although some radioactive isotopes may be formed, they are generally of short life. Some small changes in the mechanical and electrical properties of metals have been observed over the region of interest but generally they are not significant. For example, the resistivity of copper was found to increase 0.25 percent at 27 C and 30 percent at -183 C. Certain metals, such as boron and cadmium, have a great neutron affinity and hence their atoms form an excellent shield against thermal neutrons. Plating, coatings, or dispersions of these materials in a binder such as polyethylene, are being used for protective purposes. Lead and tungsten are used to absorb gamma rays.

Plastics and elastomers tend to decompose or cross link under sustained nuclear radiation. In the cross-linking process, materials such a polyethylene, polystyrene, nylon, neoprene, and silicones become more rigid, brittle, and thermostable. In fact, a limited amount of radiation improves the upper temperature limit of polyethylene, and such materials that decompose to the monomers or other degradation products are polyvinyl chloride, butyl rubber, Kel-F, and Teflon. Teflon, which has extensive use as a microwave dielectric, is particularly poor and its use must be avoided where unshielded radiation is present for extended periods of time.

Inorganic materials such as ceramics, ceramic oxide, and carbides are superior in performance to the organic materials indicated above. They can be used as rigid dielectrics or as fillers in the flexible organic materials to overcome some of their limitations. Reference 55 is the most comprehensive and latest listing on the effects of radiation on the properties of inorganic and organic materials.

DO'S AND DON'T'S

Carefully remove all fillings, loose solder, and similar foreign particles prior to assembly—cleanliness should be observed in all operations.

Seal the ends of all lines and cables during storage to prevent the ingress of moisture or dirt; protect them from dents or bruises which can cause latent operating defects.

Provide an adequate number of gas servicing vents for free circulation in pressurized systems; check for leaks periodically and make sure that the dehumidifier is operating adequately.

Avoid bending radii smaller than ten times the diameter of the cable and provide sufficient slack for shock mounted equipment; use strain relief on connectors where flexing is involved.

Separate or shield cables operating at low power levels from those carrying r-f or control power to minimize interference.

Select items from preferred or standard lists—the apparent advantages of a nonstandard item are generally offset by the maintenance of special fittings, test instrumentation, and so on.

Use the least number of waveguide couplings possible; good preformed bends or flexible assemblies can contribute less to the overall system VSWR.

Exercise extreme care in assembly and grounding of all fittings operating at high voltage to reduce corona and radiated noise; grounding should be done at several points for long runs.

Use adjustable hanger straps or clamps to relieve strain on rigid lines; use additional resilient protection such as tubing or tape wrap for cable.

Follow recommended assembly instructions for coaxial cable connectors to assure proper VSWR and voltage rating during operation.

Select items well within their electrical and thermal ratings.

Use straighteners and special bending tools for the proper installation of solid sheath, semiflexible cables.

Don't permit cable to be stored or installed in close proximity to "hot spots," such as heat dissipative tubes or resistors, steam or exhaust pipes.

Don't assemble cables with magnesium oxide dielectric without discarding the first 2 to 3 inches and drying the ends thoroughly.

Don't exert excessive forces in tightening fittings containing rubber or plastic as permanent deformation will result; occasional light retightening is preferred.

Don't specify Teflon dielectric cables (except in miniature sizes) unless the ambient temperature, or power ratings, exceed the safe values for polyethylene.

Don't force flexible waveguides beyond their natural "stop" position; contact will be broken in the guide or at the flange.

Don't subject ceramic insert pulse connectors to shock—they crack easily.

Don't apply more heat than necessary in soldering, brazing, or welding connections; where possible, use crimped connections on cable braids to prevent distortion of the dielectric.

Don't operate waveguides too close to their cutoff limits for high-power use, select a guide size so that the desired frequency will be close to midband.

COMPOSITE SYSTEMS

In the selection of a transmission line system, the equipment designed will establish certain parameters over which the component engineer has very little control, such as the frequency band, the type of signal modulation, and the power level. The overall insertion loss and the VSWR of any proposed transmission line system must be considered with respect to its effect on the power available at the antenna, the frequency stability, the re-

ceiver signal-to-noise ratio, and so on. The size, weight, and complexity of additional circuitry or auxiliary devices to overcome these deficiencies must be compared to any possible improvements in the transmission line. The transmission line and its shipping containers can be a significant factor in the volume, weight, and mobility of any tactical piece of equipment. Flexibility and simplicity of installation are always gained at the cost of greater attenuation, which may or may not be accompanied by a loss of power capability.

Lines vs. Guides

A good compromise can be achieved by a combination of transmission lines inasmuch as efficient transitions or adaptors are available for such interconnections. For minimum attenuation and maximum power, waveguides should be used. However, these parameters are established once a frequency range and cross section has been selected. They are limited to a frequency range of 1.4:1; this can be extended to 4.0:1 at considerable sacrifice of performance, but with a reduction in size. Auxiliary components to perform a myriad of electrical and mechanical functions are available in waveguide structures. The great majority of them will be usable over the entire waveguide band with a reasonably low VSWR. There are certain design limitations imposed on other components due to the variation of guide wavelength over the frequency range of the waveguide.

Where band width is of primary concern, coaxial lines can span four to six decades of frequency with no difficulty. They offer considerable savings in size and weight at frequencies below 1000 Mc, where waveguide dimensions become prohibitive. Coaxial lines are available over a wide size range permitting a choice of attenuation and power handling capacities that is independent of frequency up to their cutoff. Flexible coaxial cables are the most versatile in application up to approximately 10,000 Mc. A majority of the associated coaxial components will operate over the full frequency range of the line size. Design is simplified by the fact that the guide wavelength is independent of frequency and depends only on the dielectric media. Certain components are difficult to design due to the radial field configuration, and difficult to manufacture because of coaxial geometry.

In addition, special configurations of waveguides and coaxial lines are used to advantage in design and fabrication of components. For example, "strip line" consists of a flat center conductor separated from a single ground plane ("open" type) or between symmetrical ground planes ("closed" or shielded type). Strip line can be used to produce components or combinations thereof with minimum size and weight and at low cost by automatic production techniques. Data on these and other special types have not been included here as they are not considered general-purpose transmission lines.

REFERENCES

1. "Armed Services Index of RF Transmission Lines and Fittings," ASESA 49-2B (NAVSHIPS 900 - 102B).
2. Ramo and Whinnery, "Fields and Waves in Modern Radio," John Wiley & Sons, Inc., New York.
3. Sarbacher and Edson, "Hyper and Ultra High Frequency Engineering," John Wiley & Sons, Inc., New York.
4. Johnson, W. C., "Transmission Lines and Networks" McGraw-Hill Book Co., Inc., New York.
5. Moreno, T., "Microwave Transmission Design Data," McGraw-Hill Book Co., Inc., New York.
6. Collins, G. B., "Microwave Magnetrons," Radiation Laboratory Series, Vol. 6, Chap. 7, McGraw-Hill Book Co., Inc., New York.
7. Smith, P. H., "Transmission Line Calculator," Electronics, January 1939 and January 1944.
8. Wheeler, Harold A., "Formulas for the Skin Effect," IRE Proceedings, Vol. 30, pp. 412-424, September 1942. (This paper also includes an excellent list of references.)
9. Tearo, B. R., Jr., and E. R. Schatz, "Copper-Covered Steel Wire at Radio Frequencies," IRE Proceedings, Vol. 32, pp. 397-403, July 1944.
10. Ragan, G. L., "Microwave Transmission Circuits," Chap. 3, McGraw-Hill Book Co., Inc., New York.
11. Davis, R., A. E. W. Austin, and Willis Jackson, "The Voltage Characteristics of Polyethylene Cables," Journal IEE, Part III, p. 154, May 1947.
12. "Thermoplastic Insulated Pulse Cables," Final Report, Contract W-36-039-SC-44519, Federal Telecommunication Laboratories, Inc., Nutley, New Jersey.

13. Mildner, R. C., "The Power Rating of Radio Frequency Cables," AIEE Proceedings, Section T 978, Vol. 68, 1949.
14. Macalpine, W. M., "Heating of Radio Frequency Cables," AIEE Proceedings, Section T 977, Vol. 68, 1949.
15. Ragan, G. L., op. cit., pp. 160-169.
16. Schelkunoff, S. A., "Electromagnetic Theory of Coaxial Lines and Cylindrical Shields," Bell System Technical Journal, Vol. 13, 1934.
17. Camillo, C., and G. J. Mares, "Guide to the Selection of RF Cables," Tele-Tech and Electronic Industries, July 1956.
18. Suverkrop, Capt. B., "Derating Factors of RF Cables," WADC Coaxial Cable Meeting, February 1957.
19. Birenbaum, L., S. Greenblatt, and J. W. E. Griemsmann, "Measurement of Energy Leakage from Radio Frequency Cables at VHF and Microwave Frequencies," AIEE Conference Paper 56-563.
20. Gooding, F. H., and H. B. Slade, "Shielding of Communication Cables," AIEE Transactions, Paper 55-198.
21. "Reference Data for Radio Engineers," 4th Edition, pp. 589-591, Federal Telephone & Radio Corp.
22. Mariotti, P. A., "Broadband, Bead Supported Coaxial Lines and Fittings," Final Report R-393-54 PIB-329, Polytechnic Institute of Brooklyn.
23. Ragan, G. L., op. cit., p. 151.
24. Merrell, E. J., A. L. McKean, and J. Arbuthnott, Jr., "Styroflex Aluminum Sheath Air Dielectric Cable," AIEE Transactions, Paper 56-803.
25. Mildner, R. C., and R. J. Slaughter, "The Electrical and Mechanical Characteristics of Helical Membrane Cable," presented at Wire & Cable Symposium, Asbury Park, New Jersey, December 1955.
26. Brown, J. S., "Flexible Air Dielectric Coaxial Cable," Tele-Tech and Electronic Industries, May 1955.
27. Griemsmann, J. W. E., "An Approximate Analysis of Coaxial Line with a Helical Dielectric Support," IRE Transactions, Vol. MTT-4, January 1956.
28. Blaisdell, Kenneth L., "General Characteristics, Handling and Installation of Pyrotenax Coaxial RF Cables," U. S. Navy Underwater Sound Laboratory Report No. 91, 5 January 1948.
29. "Reference Data for Radio Engineers," op. cit., pp. 958-963.
30. Mares, G. J., and N. J. Sladek, "Subminiature Coaxial Cable RF Power Ratings and Connector Characteristics," presented at Wire & Cable Symposium, Asbury Park, New Jersey, December 1955.
31. "Development of Suitable Production Techniques for R. F. Cables of Special Uniform Impedance Techniques," Final Engineering Report Contract NObsr-42099, Amphenol Electronics Corp., Chicago.
32. Griemsmann, J. W. E., and S. W. Rosenthal, "Measurement of Radio Frequency Cable," Final Report R-408-54 PIB-341 Contract NObsr -63084, Polytechnic Institute of Brooklyn.
33. Maupin, J. T., "Interaxial Spacing and Dielectric Constant of Multipaired Cables," Bell System Technical Journal, July 1951.
34. "Balanced R. F. Cables," Final Engineering Report, Contract DA 36-039-SC-15392, Amphenol Electronics Corp., Chicago.
35. Tenzer, M. and J. Spergel, "Thermoplastic Triaxial Pulse Cables," National Electronics Conference, Chicago, 1953.
36. "An Investigation of Interference from Radar Modulators," 5th & 6th Quarterly Reports, Contract AF 30(602)-401, Rensselaer Polytechnic Institute, Troy, New York.
37. Agrios, J., and R. G. Feller, "High Power, Low Noise Pulse Cable," presented at the Wire & Cable Symposium, Asbury Park, New Jersey, 1956.
38. "Development of High Attenuation, High Power Radio Frequency Cable," Final Engineering Report, Contract NObsr-39416, Amphenol Electronics Corp., Chicago.
39. "Electromagnetic Delay Line," Final Report, Contract DA 36-039-SC-52041, Federal Telecommunications Laboratory, Nutley, New Jersey, July 1954.
40. "Anti-Noise Cable," Technical Memorandum No. 4, Contract W-64-167-eng-1336, Engineering Research Associates, Inc., Arlington, Virginia, May 1949.
41. Perls, T. A., "Electrical Noise from Instrument Cables Subjected to Shock and Vibration," Journal of Applied Physics, Vol. 23, No. 6, pp. 674-680, June 1952.
42. Marcuvitz, Nathan, "Waveguide Handbook," MIT Radiation Laboratory Series, Vol. 10, McGraw-Hill Book Co., Inc., New York.
43. "American Standard Definitions of Terms on Antennas and Waveguides," ASA Standard C-16.21, 1954. IRE Proceedings Vol. 41 No. 12, December 1953.
44. Hopfer, Samuel, "Design of Ridged Waveguide," IRE Transactions on Microwave Theory and Techniques, Vol. MTT-3, No. 5, October 1955.

45. Lending, H. D., "New Criteria for Microwave Component Surfaces," National Electronics Conference, Chicago, 1954.
46. Gould, L., "Handbook on Breakdown of Air in Waveguide Systems," Index No. NE 111616, Navy Dept, April 1956.
47. "Development of Magnesium Waveguides and Flanges," Final Report, Contract AF 33(038)-14347, Model Engineering and Manufacturing Co., Huntington, Indiana, April 1953.
48. Miller, S. E., "Notes on Methods of Transmitting the Circular Electric Wave Around Bends," Proc. IRE, Vol. 40, pp. 1104-1113, September 1952.
49. "Basic Design Criteria for Circular Waveguide Components," Final Report, Contract DA-36-039-SC-5518, Microwave Associates, Inc., Boston, March 1954.
50. Beck, A. C., and S. E. Miller, "Low Loss Waveguide Transmission," Proc. IRE, Vol. 41, pp. 348-358, March 1953.
51. "Extremely Broadband Component Development," Final Report No. 9.01, Contract DA-36-039-SC-42662, Polytechnic Research and Development Co., Inc., Brooklyn, New York, August 1954.
52. Anderson, T. N., "Double-Ridge Waveguide for Commercial Airlines Weather Radar Installations," IRE Transactions on Microwave Theory and Techniques, Vol. MTT-3, No. 4, July 1955.
53. "Flexible Waveguide Manual," Navy Dept Publication Navships 900,150, Technicraft Laboratories, Inc., Thomaston, Conn.
54. "Final Report on Broadband Waveguide Couplings," Report No 5224-1184, Contract No. W-36-039-SC-36855, Sperry Gyroscope Co., Great Neck, New York, April 1950.
55. Bopp, C. D., and O. Sisman, "Radiation Stability of Plastic and Elastomers," Nucleonics 13(7), pp. 28-33, July 1955.
56. Southworth, "Principles and Applications of Waveguide Transmission."
57. Wind, M., and H. Rapport editors, "Handbook of Microwave Measurements," Brooklyn Polytechnic Institute, 1954, distributed by Interscience Pub., Inc., New York.

APPENDIX

The following tables summarize the mechanical and electrical details of batteries made in accordance with military specifications. They are presented to give the designer a cross reference to military battery specifications and to help him select a military specification under which he may purchase a battery when he knows its characteristics.

The reader should note that the data in these tables as well as in the text of this book represent information from the specifications, their amendments, supplements and associated publications as of 1957. Because the specifications are under constant review and change to keep them abreast of advances in battery design and manufacture, the designer should refer to the latest issue of these publications.

Table I — Single Unit Military Batteries, Electrical and Mechanical Details

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, oz max)	Discharge rate or capacity	Test end voltage (volts)	Type
			Terminal voltage 1 volt		
	Stud and nut	0.0882 (40 grams)	6 weekly cycles consisting of 2 sec discharge through .15 ohms at 10 min intervals for 2 hr each day for 5 consecutive days per week	0.80	BA-245/U° BA-2245/U
			Terminal voltage 1.25 volts		
D. 3/8 H. 11/32	Flat surface	0, 0.10	30 days through 5 megohms	1.0	BA-45
			Terminal voltage 1.3 volts		
L. 2-5/8 W. 1-5/16	Stud and nut	0, 14	175 hr through 10 ohms	0.9	BA-1015A/U
D. 1-5/16 H. 2-3/8	Flat surface	0, 6	2380 min through 6.67 ohms for 4 min each 1/2 hr, 10 hr per day, 5 days per week	0.98	BA-1030/U
L. 2-5/8 W. 2-5/8 H. 4	Stud and nut	1, 8	175 hr through 5 ohms for 2 periods of 1 hr each, daily. Interval between discharges, 6 and 16 hr	0.9	BA-1035/U
D. 1-11/32 H. 6-1/8	Flat surface	0, 11	30 hr through 5 ohms	1.0	BA-1037/U
L. 2-7/16 W. 1-5/16 H. 4-9/16	Socket	1, 6	30 days through 65 ohms	1.25	BA-1277/U
			Terminal voltage 1.5 volts		
L. 2-5/8 W. 1-5/16 H. 4	Stud and nut	0, 14	90 hr through 10 ohms	0.9	BA-15A
D. 2-9/16 H. 6	Stud and nut	2, 5	85 hr through 2-2/3 ohms for 2 periods of 1 hr each, daily. Interval between discharges 6 and 16 hr	0.85	BA-29
D. 1-5/16 H. 2-3/8	Flat surface	0, 4	1120 min through 6 ohms for 4 min each 1/2 hr, 10 hr per day, 5 days per week	0.93	BA-30
L. 2-5/8 W. 2-5/8 H. 4	Stud and nut	1, 8	125 hr through 5 ohms for 2 periods of 1 hr each, daily. Interval between discharges 6 and 16 hr	0.9	BA-35
D. 1-11/32 H. 6-1/8	Flat surface	0, 11	18 hr through 5 ohms	1.0	BA-37
D. 1 H. 1-3/4	Flat surface	0, 2	480 min through 7.5 ohms for 4 min each hour, 10 hr per day, 5 days per week	0.93	BA-42
D. 9/16 H. 1-13/16	Flat surface	0, 0.6	480 min through 20 ohms for 4 min each hour, 10 hr per day, 5 days per week	0.93	BA-58
L. 2-5/8 W. 2-5/8 H. 4	Socket	1, 8	125 hr through 5 ohms for 2 periods of 1 hr each, daily. Interval between discharges 6 and 16 hr	0.9	BA-65
D. 1-5/16 H. 2-1/4	Flat surface	0, 4	60 cycles consisting of 10 discharges through 0.15 ohm at 2 min intervals each hr; 9 discharges are for 1 sec each; the 10th is for 2 sec	0.5	BA-202/U?
D. 1-5/16 H. 4	Socket	0, 8	100 hr through 5 ohms	0.9	BA-231/U
D. 2-9/16 H. 6	Stud and nut	2, 6	Initial: 76 hr through 2-2/3 ohms for 2 periods of 1 hr each, daily. Interval between discharges 6 and 16 hr. Arctic: above discharge for 7 hr	0.85	BA-2029/U

Table I—Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, oz max)	Discharge rate or capacity	Test end voltage (volts)	Type
Terminal voltage 1.5 volts (cont)					
D. 1-5/16 H. 2-3/8	Flat surface	0, 4	Initial: 960 min through 6.67 ohms for 4 min each 1/2 hr, 10 hr per day, 5 days per week Arctic: above discharge for 96 min	0.93	BA-2030
L. 2-5/8 W. 2-5/8 H. 4	Stud and nut	1, 8	Initial: 112 hr through 5 ohms for 2 periods of 1 hr each, daily. Interval between discharges 6 and 16 hr Arctic: above discharge for 11 hr	0.9	BA-2035/U
D. 1-11/32 H. 6-1/8	Flat surface	0, 11	Initial: 16 hr through 5 ohms Arctic: 1.6 hr through 5 ohms	1.0	BA-2037/U
D. 1 H. 1-3/4	Flat surface	0, 2	Initial: 400 min through 7.5 ohms for 4 min each hr, 10 hr per day, 5 days per week Arctic: above discharge for 40 min	0.93	BA-2042/U
D. 9/16 H. 1-13/16	Flat surface	0, 0.5	Initial: 320 min through 20 ohms for 4 min each hr, 10 hr per day, 5 days per week Arctic: above discharge for 32 min	0.93	BA-2053/U
L. 2-5/8 W. 2-5/8 H. 4	Socket	1, 8	Initial: 112 hr through 5 ohms for 2 periods of 1 hr each, daily. Interval between discharges 6 and 16 hr Arctic: above discharge for 11 hr	0.9	BA-2065/U
D. 1-5/16 H. 3-7/16	Flat surface	0, 7	18 hr through 5 ohms for 4 hr daily	0.9	BA-401/U
L. 2-5/8 W. 1-3/8 H. 4-1/2	Socket	0, 15	18 hr through 2.5 ohms for 4 hr daily	0.9	BA-402/U
L. 3-15/16 W. 1-3/8 H. 4-1/2	Socket	1, 3	18 hr through 1.66 ohms for 4 hr daily	0.9	BA-403/U
L. 2-5/8 W. 2-5/8 H. 4-1/2	Socket	1, 10	18 hr through 1.25 ohms for 4 hr daily	0.9	BA-404/U
L. 3-15/16 W. 2-5/8 H. 4-1/2	Socket	2, 6	18 hr through 0.83 ohm for 4 hr daily	0.9	BA-405/U
L. 2-5/8 W. 1-5/16 H. 4	Stud and nut	0, 16	Initial: 81 hr through 10 ohms Arctic: 8 hr through 100 ohms	0.9	BA-2015A/U
L. 2-5/8 W. 1-3/8 H. 4-1/2	Socket	0, 15	Initial: 16 hr through 2.5 ohms for 4 hr daily Arctic: above discharge for 1.6 hr	0.9	BA-2402/U
L. 3-15/16 W. 1-3/8 H. 4-1/2	Socket	1, 3	Initial: 16 hr through 1.66 ohms for 4 hr daily Arctic: above discharge for 1.6 hr	0.9	BA-2403/U
L. 2-5/8 W. 2-5/8 H. 4-1/2	Socket	1, 10	Initial: 16 hr through 1.25 ohms for 4 hr daily Arctic: above discharge for 1.6 hr	0.9	BA-2404/U
L. 3-15/16 W. 2-5/8 H. 4-1/2	Socket	2, 6	Initial: 16 hr through 0.83 ohms for 4 hr daily Arctic: above discharge for 1.6 hr	0.[illegible]	BA-2405/U
L. 1.06 W. 0.43 H. 1.69	Stud and nut	0.061, –	22 amp min (1)*	1.0	BA-426/U†

*MIL-B-13136(SigC). Numbers in parentheses appearing [illegible] above table refer to notes on page 344.
†MIL-B-14385(SigC)

Table I—Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, or max)	Discharge rate or capacity	Test end voltage (volts)	Type
Terminal voltage 1.5 volts (cont)					
L. 1.21 W. 0.49 H. 1.85	Stud and nut	0.085, -	59 amp min (1)	1.0	BA-427/U†
L. 1.38 W. 0.56 H. 2.10	Stud and nut	0.133, -	74 amp min (1)	1.0	BA-428/U†
L. 1.58 W. 0.64 H. 2.39	Stud and nut	0.216, -	124 amp min (1)	1.0	BA-429/U†
L. 1.76 W. 0.71 H. 2.64	Stud and nut	0.304, -	160 amp min (1)	1.0	BA-430/U†
L. 1.95 W. 0.79 H. 2.95	Stud and nut	0.387, -	240 amp min (1)	1.0	BA-431/U†
L. 2.20 W. 0.89 H. 3.32	Stud and nut	0.606, -	290 amp min (1)	1.0	BA-432/U†
L. 2.47 W. 1.00 H. 3.73	Stud and nut	0.889, -	340 amp min (1)	1.0	BA-433/U†
L. 2.81 W. 1.13 H. 4.33	Stud and nut	1.32, -	390 amp min (1)	1.0	BA-434/U†
L. 3.15 W. 1.28 H. 4.78	Stud and nut	1.83, -	610 amp min (1)	1.0	BA-[illegible]/U†
L. 3.65 W. 1.47 H. 5.49	Stud and nut	3.13, -	980 amp min (1)	1.0	BA-436/U†
L. 1.06 W. 0.43 H. 1.60	Stud and nut	0.061, -	50 amp min (2)	1.1	BA-437/U†
L. 1.21 W. 0.49 H. 1.85	Stud and nut	0.85, -	82 amp min (2)	1.1	BA-438/U†
L. 1.38 W. 0.56 H. 2.10	Stud and nut	0.133, -	125 amp min (2)	1.1	BA-439/U†
L. 1.58 W. 0.64 H. 2.39	Stud and nut	0.218, -	200 amp min (2)	1.1	BA-440/U†
L. 1.76 W. 0.71 H. 2.64	Stud and nut	0.291, -	250 amp min (2)	1.1	BA-441/U†
L. 1.95 W. 0.79 H. 2.95	Stud and nut	0.453, -	430 amp min (2)	1.1	BA-442/U†
L. 2.20 W. 0.89 H. 3.32	Stud and nut	0.593, -	600 amp min (2)	1.1	BA-443/U†
L. 2.47 W. 1.00 H. 3.73	Stud and nut	0.843, -	900 amp min (2)	1.1	BA-444/U†

†MIL-B-14396(SigC)

Table I—Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, oz max)	Discharge rate or capacity	Test end voltage (volts)	Type
Terminal voltage 1.5 volts (cont)					
L. 2.81 W. 1.13 H. 4.23	Stud and nut	1.38, -	1100 amp-min (2)	1.1	BA-405/U†
L. 3.16 W. 1.20 H. 4.76	Stud and nut	1.93, -	1850 amp min (2)	1.1	BA-406/U†
L. 3.63 W. 1.47 H. 5.49	Stud and nut	3.24, -	2650 amp min (2)	1.1	BA-407/U†
Terminal voltage 2.6 volts					
L. 1-3/8 W. 11/16 H. 2-1/4	Flat spring	0, 4	250 hr through 330 ohms	2.2	BA-1203/U
Terminal voltage 3 volts					
L. 1-1/8 W. 9/16 H. 2	Coil spring and flat surface (3)	0, 1.5	28 min through 12 ohms	1.8	BA-59
L. 2-5/8 W. 1-5/16 H. 4-3/16	Socket	0, 14	35 min through 1.6 ohms, for 1 min each hr, 10 hr per day, 5 days per week	1.8	BA-204/U
L. 2-5/8 W. 3-5/16 H. 3-15/16	Stud and nut	0, 14	20 hr through 20 ohms	2.0	BA-205/U
L. 1-3/8 W. 11/16 H. 2-1/4	Flat spring	0, 4	80 hr through 330 ohms	2.2	BA-206/U
D. 1 H. 3-3/4	Flat surface	0, 3.5	480 min through 150 ohms for 4 min each hr, 10 hr per day, 5 days per week	1.87	BA-209/U
L. 3-7/8 W. 2-5/8 H. 5-1/2	Spring clip	3, 4	140 hr through 15 ohms	1.8	BA-225/U
L. 1-1/8 W. 1-1/8 H. 2-3/8	Socket	0, 3	70 min through 7.5 ohms for 1 min every 2 hr	2.2	BA-227/U
L. 5-1/4 W. 5-1/4 H. 6-13/16	Stud and nut	10, 0	70 hr through 2 2/3 ohms for 2 periods of 1 hr each, daily. Intervals between discharge 6 and 16 hr	1.7	BA-242/U
L. 1-21/32 W. 37/32 H. 2-21/32	Wire leads with spade lugs (4)	0, 4	365 days through 300,000 ohms	3.0	BA-251/U
L. 2-5/8 W. 1-3/8 H. 3-3/16	Socket (4)	0, 9	15 hr through 20 ohms for 4 hr daily	1.8	BA-406/U
L. 2-5/8 W. 1-3/8 H. 4-1/2	Socket (4)	0, 13	18 hr through 10 ohms for 4 hr daily	1.8	BA-407/U
L. 2-5/8 W. 1-5/16 H. 4-3/16	Socket	0, 14	Initial: 31 min through 1.6 ohms for 1 min each hr, 10 hr per day, 5 days per week Arctic: above discharge for 3.5 min	1.8	BA-2204/U
L. 2-5/8 W. 1-5/16 H. 3-15/16	Stud and nut	0, 14	Initial: 18 hr through 20 ohms Arctic: 1.8 hr through 20 ohms	2.0	BA-2205/U

†MIL-B-14396(SigC)

Table I—Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, oz max)	Discharge rate or capacity	Test end voltage (volts)	Type
			Terminal voltage 3 volts (cont)		
L. 1-3/8 W. 11/16 H. 2-1/4	Flat spring	0, 4	Initial: 72 hr through 330 ohms Arctic: 7 hr through 330 ohms	2.2	BA-2226/U
L. 3-7/8 W. 2-5/8 H. 5-1/2	Spring clip	3, 4	Initial: 120 hr through 15 ohms Arctic: 12 hr through 15 ohms	1.8	BA-2225/U
L. 2-5/8 W. 1-3/8 H. 3-3/16	Socket (4)	0, 9	Initial: 13.5 hr through 20 ohms for 4 hr daily Arctic: above discharge for 1.3 hr	1.8	BA-2406/U
L. 2-5/8 W. 1-3/8 H. 4-1/2	Socket (4)	0, 15	Initial: 16 hr through 10 ohms for 4 hr daily Arctic: above discharge for 1.6 hr	1.8	BA-2407/U
			Terminal voltage 3.9 volts		
L. 1-31/32 W. 21/32 H. 2-1/4	Flat spring	0, 5	1600 min through 50 ohms for 4 min each hr, 10 hr per day, 5 days per week	2.8	BA-1078/U
			Terminal voltage 4.5 volts		
L. 2-7/16 W. 13/16 H. 2-9/16	Flat spring	0, 6	320 min through 20 ohms for 4 min each hr, 10 hr per day, 5 days per week	2.8	BA-9
L. 4 W. 1-7/16 H. 3-1/16	Stud and nut (5)	1, 0	1200 min through 20 ohms for 4 min each hr, 10 hr per day, 5 days per week	2.8	BA-27
L. 1-31/32 W. 21/32 H. 2-1/4	Flat spring	0, 5	420 min through 50 ohms for 4 min each hr, 10 hr per day, 5 days per week	2.8	BA-30
L. 2-7/16 W. 13/16 H. 2-11/16	Stud and nut	0, 5	320 min through 20 ohms for 4 min each hr, 10 hr per day, 5 days per week	2.8	BA-31
L. 3-7/8 W. 3-7/8 H. 3-5/8	Spring clip	4, 8	125 hr through 15 ohms for 2 periods of 1 hr each, daily. Interval between discharges 6 and 16 hr	2.7	BA-216/U
L. 3-15/16 W. 1-5/16 H. 4-5/8	Socket	1, 6	90 hr through 75 ohms	3.3	BA-225/U
L. 4 W. 1-7/16 H. 3-1/16	Stud and nut (5)	1, 0	Initial: 1090 min through 20 ohms for 4 min each hr, 10 hr per day, 5 days per week Arctic: above discharge for 108 min	2.8	BA-2027
L. 1-31/32 W. 21/32 H. 2-1/4	Flat spring	0, 5	Initial: 376 min through 50 ohms for 4 min each hr, 10 hr per day, 5 days per week Arctic: Above discharge for 5 min	2.8	BA-2028
L. 2-7/16 W. 13/16 H. 2-11/16	Stud and nut	0, 6	Initial: 328 min through 20 ohms for 4 min each hr, 10 hr per day, 5 days per week Arctic: above discharge for 8 min	2.8	BA-2031/U
			Terminal voltage 6.0 volts		
L. 10-3/8 W. 2-11/16 H. 6-3/4	Stud and nut	10, 0	85 hr through 10-2/3 ohms for 2 periods of 1 hr each, daily. Intervals between discharge 6 and 16 hr	3.4	BA-44
L. 2-5/8 (8) W. 2-5/8 H. 3-7/8	Two coil springs	1, 8	20 hr through 40 ohms	4.0	BA-200/U

Table I—Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, oz max)	Discharge rate or capacity	Test end voltage (volts)	Type
Terminal voltage 6.0 volts (cont)					
L. 3-7/8 W. 2-23/32 H. 5-1/2	Socket	3, 4	125 hr through 40 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr	3.6	BA-2[illegible]/U
L. 2-5/8 W. 2-5/8 H. 4	Socket	1, 8	20 hr through 40 ohms	4.0	BA-21[illegible]
L. 8-3/16 W. 2-11/16 H. 5-3/4	Stud and nut	5, 6	125 hr through 20 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr	3.6	BA-222/U
L. 10-3/8 W. 2-11/16 H. 6-3/4	Stud and nut	10, 0	75 hr through 10-2/3 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr	3.4	BA-2[illegible]/U
L. 2-5/8 W. 2-5/8 H. 3-3/16	Socket (7)	1, 2	18 hr through 40 ohms for 4 hr daily	3.6	BA-4[illegible]/U
L. 2-5/8 (d) W. 2-5/8 H. 3-7/8	Two coil springs	1, 0	Initial: 18 hr through 40 ohms Arctic: 1.8 hr through 40 ohms	4.0	BA-2[illegible]/U
L. 3-7/8 W. 2-23/32 H. 5-1/2	Socket	3, [illegible]	Initial: 112 hr through 40 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr Arctic: above discharge for 11 hr	3.6	BA-22[illegible]/U
L. 2-5/8 W. 2-5/8 H. 4	Socket	1, 0	Initial: 18 hr through 40 ohms Arctic: 1.8 hr through 40 ohms	4.0	BA-22[illegible]/U
L. 8-3/16 W. 2-11/16 H. 5-3/4	Stud and nut	5, 6	Initial: 112 hr through 20 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr Arctic: above discharge for 11 hr	3.6	BA-2222/U
L. 2-5/8 W. 2-5/8 H. 4-1/2	Socket (7)	1, 10	18 hr through 20 ohms for 4 hr daily	3.6	BA-409/U
L. 5-1/4 W. 2-11/16 H. 4-1/2	Socket (7)	3, 5	18 hr through 10 ohms for 4 hr daily	3.6	BA-410/U
L. 5-3/8 W. 3-7/8 H. 6	Socket (7)	6, 6	18 hr through 5 ohms for 4 hr daily	3.6	BA-411/U
L. 7-13/16 W. 3-7/8 H. 6	Socket (7)	9, 12	18 hr through 3.33 ohms for 4 hr daily	3.6	BA-412/U
L. 2-5/8 W. 2-5/8 H. 3-3/16	Socket (7)	1, 2	Initial: 13.5 hr through 40 ohms for 4 hr daily Arctic: above discharge for 1.3 hr	3.6	BA-2408/U
L. 2-5/8 W. 2-5/8 H. 4-1/2	Socket (7)	1, 10	Initial: 16 hr through 20 ohms for 4 hr daily Arctic: above discharge for 1.6 hr	3.6	BA-2409/U
L. 5-1/4 W. 2-11/16 H. 4-1/2	Socket (7)	3, 5	Initial: 16 hr through 10 ohms for 4 hr daily Arctic: above discharge for 1.6 hr	3.6	BA-2410/U
L. 5-3/8 W. 3-7/8 H. 6	Socket (7)	6, 6	Initial: 16 hr through 5 ohms for 4 hr daily Arctic: above discharge for 1.6 hr	3.6	BA-2411/U

Table I—Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, oz max)	Discharge rate or capacity	Test end voltage (volts)	Type
Terminal voltage 6.0 volts (cont)					
L. 7-13/16 W. 3-7/8 H. 6	Socket (7)	9, 12	Initial: 16 hr through 3.33 ohms for 4 hr daily. Arctic: above discharge for 1.6 hr	3.6	BA-2412/U
Terminal voltage 6.5 volts					
L. 3-7/8 W. 2-23/32 H. 5-1/2	Socket	3, 4	150 hr through 40 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr	3.6	BA-1203/U
L. 2-3/8 W. 2-5/8 H. 4	Socket	1, 8	65 hr through 40 ohms	4.0	BA-1210/U
L. 6-3/16 W. 2-11/16 H. 5-3/4	Stud and nut	5, 6	143 hr through 20 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr	3.6	BA-1222/U
Terminal voltage 7.5 volts					
L. 4-1/16 W. 7/8 H. 2-13/16	Stud and nut and 1 wire lead (8)	0, 10	320 min through 35 ohms for 4 min each hr, 10 hr per day, 5 days per week	4.5	BA-34
L. 4-1/16 W. 7/8 H. 2-13/16	Stud and nut and 1 wire lead (8)	0, 10	Initial: 300 min through 35 ohms for 4 min each hr, 10 hr per day, 5 days per week. Arctic: above discharge for 28.0 min	4.5	BA-2034/U
L. 2.25 W. 2 H. 2.030	Stud and nut	1, 0	15 min through 1.52 ohms, 3.5 min through 0.37 ohm, 1 min through 0.17 ohm	6.3	5-15AZ‡
L. 3.625 W. 3.250 H. 4.625	Stud and nut	3.25, 0	30 min through 0.315 ohm, 15 min through 0.243 ohm, 5 min through 0.117 ohm	6.3	90-15AZ‡
Terminal voltage 9.0 volts					
L. 7-13/16 W. 5-5/16 H. 6-3/4	Stud and nut	15, 8	85 hr through 16 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr	5.1	BA-206/U
L. 8-1/2 W. 4 H. 5-7/8	Stud and nut	9, 8	60 hr through 16 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr	5.1	BA-207/U
L. 7-13/16 W. 5-1/4 H. 6-13/16	Stud and nut	15, 8	79 hr through 16 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr	5.1	BA-256/U (9)
Terminal voltage 13 volts					
D. 23/32 H. 4-9/16	Wire leads (10)	--	55 hr through 22,000 ohms for 13-volt section and 22 ohms for 1.3-volt section for 7 hr per day, 5 days per week	Terminal 9 Tap 0.9	--¶
Terminal voltage 13.5 volts					
L. 7-13/16 W. 7-13/16 H. 6-13/16	Wire leads with eyelugs	23, 8	70 hr through 24 ohms for 2 periods of 1 hr each, daily. Intervals between discharges 6 and 16 hr	7.65	BA-223/U (9)
Terminal voltage 22.5 volts					
L. 3-7/16 W. 2-1/32 H. 2-19/32	Wire leads	1, 4	90 hr through 2500 ohms	17	BA-2

‡MIL-B-7155B(ASG)
¶MIL-B-18550A(USAF)

Table I — Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, oz max)	Discharge rate or capacity	Test end voltage (volts)	Type
Terminal voltage 22.5 volts (cont)					
L. 6-9/16 W. 4 H. 3	Wire leads	4, 8	320 hr through 1250 ohms	17	BA-8
L. 4-1/16 W. 2-17/32 H. 2-15/16	Socket (11)	1, 12	70 hr through 1500 ohms	17	BA-311/U
L. 4-1/8 W. 2-1/2 H. 2-11/16	Spring clip (12)	1, 12	70 hr through 1500 ohms	17	BA-230/U
L. 1-9/16 W. 1-5/16 H. 2-15/16	Socket	0, 5	400 hr through 22,500 ohms for 5 hr per day, 5 days per week	15	BA-232/U
L. 1 W. 5/8 H. 1-15/16	Flat surface	0, 1.33	50 hr through 22,500 ohms for 4 hr per [illegible], 5 days per week	17	BA-[illegible]1/U
L. 1-9/16 W. 1-7/16 H. 3-1/4	Socket	0, 6	18 hr of cycle consisting of 2 min through 1300 ohms and 18 min through 3300 ohms for 4 hr daily	16.5	BA-413/U
L. 2-3/8 W. 2-1/4 H. 4-1/8	Socket	1, 1	20 hr of cycle consisting of 2 min through 400 ohms and 18 min through 900 ohms for 4 hr daily	16.5	BA-417/U
L. 2-9/16 W. 2-1/2 H. 4-5/8	Socket	1, 10	14 hr of cycle consisting of 2 min through 300 ohms and 18 min through 700 ohms for 4 hr daily	16.5	BA-431/U
L. 3-7/16 W. 2-1/32 H. 2-19/32	Wire leads	1, 4	Initial: 81 hr through 2500 ohms Arctic: 3 hr through 2500 ohms	17.8	BA-20[illegible]
L. 4-1/8 W. 2-1/2 H. 2-11/16	Spring clip (12)	1, 12	Initial: 65 hr through 1500 ohms Arctic: 6 hr through 1500 ohms	17.0	BA-2230/U
L. 1-9/16 W. 1-5/16 H. 2-15/16	Socket	0, 5	Initial: 330 hr through 22,500 ohms for 5 hr per day, 5 days per week	15.0	BA-2232/U
L. 1-9/16 W. 1-7/16 H. 3-1/4	Socket	0, 6	Initial: 14 hr of cycle consisting of 2 min through 1300 ohms and 18 min through 3300 ohms for 4 hr daily Arctic: above discharge for 1.4 hr	16.5	BA-2413/U
L. 2-3/8 W. 2-1/4 H. 4-1/8	Socket	1, 1	Initial: 18 hr of cycle consisting of 2 min through 400 ohms and 18 min through 900 ohms for 4 hr daily Arctic: above discharge for 1.8 hr	16.5	BA-2417/U
L. 2-9/16 W. 2-1/2 H. 4-5/8	Socket	1, 10	Initial: 13 hr of cycle consisting of 2 min through 300 ohms and 18 min through 700 ohms for 4 hr daily Arctic: above discharge for 1.3 hr	16.5	BA-2431/U
Terminal voltage 22.4 volts					
L. 3-7/16 W. 2-1/32 H. 2-19/32	Wire leads	1, 4	200 hr through 2500 ohms	17.0	BA-100[illegible]/U
L. 4-1/16 W. 2-17/32 H. 2-15/16	Socket (13)	1, 12	140 hr through 1500 ohms	17.0	BA-1211/U

Table I — Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, or max)	Discharge rate or capacity	Test end voltage (volts)	Type
Terminal voltage 23.4 (cont)					
L. 1-9/16 W. 1-5/16 H. 2-15/16	Socket	0.5	690 hr through 22,500 ohms for 5 hr per day, 5 days per week	15.0	BA-1232/U
Terminal voltage 29 volts					
L. 6.14 W. 2.8 H. 2.03	Stud and nut	2.9, - (approx)	25 amp min at 1 min rate	24.0	BA-234/U‡
L. 8-11/16 W. 3-15/16 H. 3-1/32	Stud and nut	7.9, - (approx)	190 amp min [illegible] 1 min rate	24.0	BA-235/U
Terminal voltage 30 volts					
L. 3.00 W. 0.543 H. 0.68	Wire lead	0.066, -	0.425 amp min (14)	22.0	BA-448/U†
L. 3.00 W. 0.605 H. 0.75	Wire lead	0.081, -	0.70 amp min (14)	22.0	BA-449/U†
L. 2.87 W. 0.67 H. 0.81	Snap on	0.095, -	1.3 amp min (14)	22.0	BA-450/U†
L. 2.87 W. 0.77 H. 0.99	Snap on	0.115, -	1.95 amp min (14)	22.0	BA-451/U†
L. 2.87 W. 0.90 H. 1.02	Snap on	0.159, -	3.25 amp min (14)	22.0	BA-452/U†
L. 0.287 W. 1.05 H. 1.17	Snap on	0.249, -	5 amp min (14)	22	BA-453/U†
L. 0.287 W. 1.40 H. 1.33	Snap on	0.390, -	8 amp min (14)	22	BA-454/U†
L. 0.287 W. 1.49 H. 1.61	Snap on	0.537, -	13.75 amp min (14)	22	BA-455/U†
L. 0.287 W. 1.80 H. 1.93	Snap on	[illegible].11, -	21 amp min (14)	22	BA-456/U†
L. 0.287 W. 2.24 H. 2.36	Snap on	1.21, -	32.5 amp min (14)	22	BA-457/U†
L. 0.287 W. 2.68 H. 2.80	Snap on	1.73, -	47.5 amp min (14)	22	BA-458/U†
L. 0.287 W. 3.18 H. 3.30	Snap on	2.73, -	72.5 amp min (14)	22	BA-459/U†
L. 0.287 W. 4.05 H. 4.18	Snap on	4.25, -	105 amp min (14)	22	BA-460/U†

† MIL-B-16556(SigC)
‡ MIL-B-11573(SigC)

Table I — Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, oz max)	Discharge rate or capacity	Test end voltage (volts)	Type
			Terminal voltage 30.8 volts		
L. 9.5 W. 9 H. 4.7	Stud and nut	38, - (approx)	1500 amp min (2)	25.2	BA-283/U ‡
			Terminal voltage 33 volts		
L. 2 W. 1-5/16 H. 2-15/16	Socket	0, 6	400 hr through 30,000 ohms for 5 hr per day, 5 days per week	22	BA-233/U
			Terminal voltage 33.8 volts		
L. 2 W. 1-5/16 H. 2-15/16	Socket	0, 6	600 hr through 30,000 ohms for 5 hr per day, 5 days per week	22	BA-1233/U
			Terminal voltage 45 volts		
L. 8-1/8 W. 4-3/8 H. 7-1/4	Spring clip (4)	13, 12	330 hr through 200 ohms	34	BA-23
L. 4-3/16 W. 2-1/2 H. 5-13/16	Stud and nut (4)	3, 6	[illegible]0 hr through 3000 ohms	34	BA-35
L. 3 W. 1-7/8 H. 4-9/16	Stud and nut (4)	1, 10	25 hr through 3800 ohms	34	BA-53
L. 2-19/32 W. 31/32 H. 3-19/32	Snap on	0, 10	7.5 hr of cycle consisting of 2 min through 1300 ohms and 4 min through 3500 ohms	28	BA-56
L. 4-3/16 W. 2-5/16 H. 4-1/8	Socket (4)	2, 1	20 hr of cycle consisting of 2 min through 800 ohms and 18 min through 1800 ohms for 4 hr daily	33	BA-418/U
L. 4-1/8 W. 2-1/2 H. 5-1/2	Socket (4)	3, 3	14 hr of cycle consisting of 2 min through 640 ohms and 18 min through 1400 ohms for 4 hr daily	33	BA-422/U
L. 4-3/16 W. 2-1/2 H. 5-13/16	Stud and nut (4)	3, 6	Initial: 63 hr through 3000 ohms Arctic: 6 hr through 3000 ohms	34	BA-2035/U
L. 2-15/16 W. 2-1/4 H. 4-1/16	Socket (4)	1, 8	Initial: 20 hr through 3800 ohms Arctic: 2 hr through 3500 ohms	34	BA-2053/U
L. 3-1/2 W. 1-23/32 H. 5-7/16	Socket	2, 0	Initial: 12 hr through 1500 ohms Arctic: 1. [illegible] through 1500 ohms	34	BA-2039/U
L. 4-1/6 W. 2-9/16 H. 5-5/16	Socket (4)	3, 0	Initial [illegible] hr through 3000 ohms Arctic: 6 hr through 3000 ohms	34	BA-2229/U
L. 2 W. 1-5/16 H. 3-13/16	Socket	0, 8	Initial: 320 hr through 45,000 ohms for 5 hr per day, 5 days per week	30	BA-2234/U
L. 2-15/16 W. 1-7/16 H. 3-1/4	Socket (4)	0, 11	Initial: 1[illegible] of cycle consisting of 2 min through [illegible]000 ohms and 18 min through 6600 ohms for 4 hr daily Arctic: above discharge for 1.6 hr	33	BA-2414/U

‡MIL-B-11575(SigC)

Table 1 — Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Weight H. Height	Terminals	Weight (lb, oz max)	Discharge rate or capacity	Test end voltage (volts)	Type
Terminal voltage 45 volts (cont)					
L. 4-3/16 W. 2-5/16 H. 4-1/8	Socket (4)	2, 1	Initial: 18 hr of cycle consisting of 2 min through 800 ohms and 18 m[illegible] through 1800 [illegible]ms for 4 hr daily Arctic: above discharge for 1.8 hr	33	BA-2418/U
L. 4-1/8 W. 2-1/2 H. 5-1/2	Socket (4)	3, 3	Initial: 13 hr of cycles consisting of 2 min through 600 ohms and 18 min through 1400 ohms for 4 hr daily Arctic: above discharge for 1.3 hr	33	BA-2422/U
L. 2 W. 1-5/16 H. 3-13/16	Socket	0, 8	400 hr through 45,000 ohms for 5 hr per day, 5 days per week	30	BA-234/U
L. 3-1/2 W. 1-23/32 H. 5-7/16	Socket	2, 0	13.5 hr through 1500 ohms	34	BA-99
L. 2-15/16 W. 2-1/4 H. 4-1/16	Socket (4)	1, 8	25 hr through 3800 ohms	34	BA-63
L. 4-1/16 W. 2-9/16 H. 5-5/16	Socket (4)	3, 0	70 hr through 3000 ohms	34	BA-225/U
L. 2-15/16 W. 1-1/4 H. 3-3/4	Stud and nut (4)	1, 0	17 hr through 5000 ohms	34	BA-228/U
L. 8-1/8 W. 4-3/8 H. 7-1/4	Spring clip (4)	13, 12	Initial: 297 hr through 2000 ohms Arctic: 29 hr through 2000 ohms	34	BA-2026/U
L. 4-3/16 W. 2-1/2 H. 5-13/16	Stud and nut (4)	3, 6	Initial: 63 hr through 3000 ohms Arctic: 6 hr through 3000 ohms	34	BA-2035/U
L. 3 W. 1-7/8 H. 4-9/16	Stud and nut (4)	1, 10	Initial: 20 hr through 3800 ohms Arctic: 2 hr through 3800 ohms	34	BA-2033/U
L. 2-15/16 W. 1-7/16 H. 3-1/4	Socket (4)	0, 11	18 hr of cycle consisting of 2 min through 2600 ohms and 18 min through 6600 ohms for 4 hr daily	33	BA-414/U
Terminal voltage 46.8 volts					
L. 3-1/2 W. 1-25/32 H. 5-7/16	Socket	2, 0	34 hr through 1500 ohms	34	BA-1059/U
L. 2-15/16 W. 2-1/4 H. 4-1/6	Socket (4)	1, 8	115 hr through 3800 ohms	34	BA-1063/U
L. 2-15/16 W. 1-1/4 H. 3-3/4	Stud and nut (4)	1, 0	70 hr through 5000 ohms	34	BA-1228/U
L. 2 W. 1-5/16 H. 3-13/16	Socket	0, 8	690 hr through 45,000 ohms for 5 hr per day, 5 days per week	30	BA-1234/U
L. 3-5/8 W. 2-1/2 H. 5-13/16	Stud and nut (4)	3, 6	135 hr through 5000 ohms	35	BA-1[illegible]8/U

Table I — Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, oz max)	Discharge rate or capacity	Test end voltage (volts)	Type
Terminal voltage 46.8 volts (cont)					
L. 3 W. 1-7/8 H. 4-9/16	Stud and nut (4)	1, 10	115 hr through 3200 ohms	34	BA-1053/U
Terminal voltage 62.4 volts					
L. 2-11/16 W. 1-5/16 H. 3-19/32	Snap on	0, 14	22 hr of cycle consisting of 2 min through 2000 ohms and 4 min through 5200 ohms	42	BA-1051/U
Terminal voltage 67.5 volts					
L. 2-11/16 W. 1-5/16 H. 3-19/32	Snap on	0, 14	7.0 hr of cycle consisting of 2 min through 2000 ohms and 4 min through 5200 ohms	42	BA-51
L. 2-11/16 W. 1-5/16 H. 3-19/32	Snap on	0, 14	Initial: 6.2 hr of cycle consisting of 2 min through 200[illegible] ohms and 4 min through 5200 ohms Arctic: above discharge for 0.6 hr	42	BA-2051/U
Terminal voltage 90 volts					
L. 5-3/8 W. 1-7/16 H. 3-1/4	Socket (15)	1, 5	18 hr of cycle consisting of 2 min through 5200 ohms and 18 min through 13,200 ohms for 4 hr daily	66	BA-415/U
L. 7-5/8 W. 2-5/16 H. 4-1/8	Socket (15)	4, 1	20 hr of cycle consisting of 2 min through 1500 ohms and 18 min through [illegible]600 ohms for 4 hr daily	66	BA-419/U
L. 9 W. 2-9/16 H. [illegible]-15/16	Socket (15)	6, 6	14 hr of cycle consisting of 2 min through 1200 ohms and 18 min through 2600 ohms for 4 hr daily	66	BA-423/U
L. 5-3/8 W. 1-7/16 H. 3-1/4	Socket (15)	1, 5	Initial: 14 hr of cycle consisting of 2 min through 5200 ohms and 18 min through 13,200 ohms for 4 hr daily Arctic: above discharge for 1.4 hr	66	BA-2415/U
L. 7-5/8 W. 2-5/16 H. 4-1/8	Socket (15)	4, 1	Initial: 18 hr of cycle consisting of 2 min through 1500 ohms and 18 min through 3600 ohms for 4 hr daily Arctic: above discharge for 1.8 hr	66	BA-2419/U
L. 9 W. 2-9/16 H. 6-13/16	Socket (15)	6, 6	Initial: 13 hr of cycle consisting of 2 min through 1200 ohms and 18 min through 2[illegible]00 ohms for 4 hr daily Arctic: above discharge for 1.3 hr	66	BA-2423/U
Terminal voltage 93.6 volts					
L. [illegible]-11/32 W. 1-1[illegible]/32 H. 11-19/32	Flat surface	1, 1	20 hr of cycle consisting of 2 min through 3000 ohms and 4 min through 8000 ohms	63	BA-1058
L. [illegible]-11/32 W. 1-11/32 H. 11-19/32	Flat surface	1, 10	8.5 hr of cycle consisting of 2 min through 3000 ohms and 4 min through 8000 ohms	63	BA-38
L. 1-11/32 W. 1-11/32 H. 11-19/32	Flat surface	1, 10	8.0 hr of cycle consisting of 2 min through 3000 ohms and 4 min through 8000 ohms	63	BA-2038/U
Terminal voltage 135 volts					
L. 6-1/8 W. 5-1/2 H. 5-1/16	Stud and nut (16)	6, 8	90 hr through 15,000 ohms	10[illegible]	BA-39

Table I—Single Unit Military Batteries, Electrical and Mechanical Details (cont)

Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Terminals	Weight (lb, max)	Discharge rate or capacity	Test end voltage (volts)	Type
Terminal voltage 135 volts (cont)					
L. 10.406 W. 2.718 H. 5.875	Terminal strips (17)	10.0	115 days through 875,000 ohms	12[illegible]	BA-239/U
L. 6-1/8 W. 3-1/2 H. 5-1/16	Stud and nut (18)	6.8	230 hr through 15,000 ohms	100	BA-1033/U
L. 6-1/8 W. 3-1/2 H. 5-1/16	Stud and nut (16)	6.2	Initial: 72 hr through 15,000 ohms Arctic: 7 hr through 15,000 ohms	100	BA-2033/U
L. 4-1/8 W. 2-7/8 H. 3-1/4	Socket (19)	2.0	18 hr of cycle consisting of 2 min through 7800 ohms and 18 min through 19,800 ohms for 4 hr daily	99	BA-416/U
L. 6-5/8 W. 4-3/8 H. 4-1/8	Socket (19)	6.1	20 hr of cycle consisting of 2 min through 2400 ohms and 18 min through 5400 ohms for 4 hr daily	99	BA-420/U
L. 7-9/16 W. 4-1/8 H. 5-5/8	Socket (19)	9.9	14 hr of cycle consisting of 2 min through 1800 ohms and 18 min through 4200 ohms for 4 hr daily	99	BA-424/U
L. 4-1/8 W. 2-7/8 H. 3-1/4	Socket (19)	2.0	Initial: 14 hr of cycle consisting of 2 min through 7800 ohms and 18 min through 19,800 ohms for 4 hr daily Arctic: above discharge for 1.4 hr	99	BA-2416/U
L. 6-5/8 W. 4-3/8 H. 4-1/8	Socket (19)	6.1	Initial: 18 hr of cycle consisting of 2 min through 2400 ohms and 18 min through 5400 ohms for 4 hr daily Arctic: above discharge for 1.8 hr	99	BA-2420/U
L. 7-9/16 W. 4-1/8 H. 5-5/8	Socket (19)	9.9	Initial: 13 hr of cycle consisting of 2 min through 1800 ohms and 18 min through 4200 ohms for 4 hr daily Arctic: above discharge for 1.3 hr	99	BA-2424/U

Notes

1. At [illegible] minute rate
2. At 10 minute rate
3. Coiled spring forms screw base socket for miniature base lamp
4. Center tapped
5. Tapped at −1.5 and −3 volts
6. Corners are beveled or rounded to permit battery to pass through 3.25-in. cylinder
7. Tapped [illegible] 1.5, 3, and 4.5 volts
8. Tapped at −1.5, −3, −4.5, and −6 volts
9. Materials must be nonmagnetic except for rivets of web strap and lock washers under terminal studs
10. Tapped at 1.5 volts
11. Tapped at −3, −4.5, and −16.5 volts
12. Tapped at −3, −4.5, −6, −9, −10.5, and −16.5 volts
13. Tapped at −2.6, −3.9, and −16.9 volts
14. At 5 minute rate
15. Tapped at 22.5, 45, and 67.5 volts
16. Tapped at 45 volts
17. Tapped at 67.5 and 73.5 volts
18. Tapped at 46.8 volts
19. Tapped at 22.5, 45, 67.5, and 90 volts

Table II—Multiple Unit Batteries, Electrical and Mechanical Details in Accordance with Specification MIL-B-18B (1)*

Voltage	Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Weight (lb, oz max)	Discharge	Test end voltage (volts)	Type
A. 1.5 B. 93.6	L. 5-1/4 W. 4-3/32 H. 6-15/16	7, 12	A: 42 hr through 1.4 ohms B: 42 hr of cycle consisting of 2 min through 1560 ohms and 4 min through 2600 ohms	A: 1.1 B: 65.0	BA-1040/U
A. 1.5 B. 93.6	L. 10 W. 2-3/16 H. 4-7/8	5, 8	A: 93 hr through 5 ohms 5 hr per day, 5 days per week B: above discharge through 9000 ohms	A: 1.1 B: 65.0	BA-1030/U
A. 1.5 B. 91	D. 2 H. 8-15/16	2, 3	A: 18 hr through 2 ohms B: 18 hr through 4300 ohms	A: 1.0 B: 63.0	BA-1247/U
A. 1.5 B. [illegible]	L. 2-1/2 W. 2-11/32 H. 6-1/4	2, 4	A: 10 hr of cycle consisting of 5 min through 4.5 ohms and 5 min through 2.1 ohms B: above discharge through 10,400 ohms and 2980 ohms	A: 1.05 B: 63	BA-1254/U
A. 1.5 B. 90	L. 10 W. 2-3/16 H. 4-7/8	5, 8	A: 90 hr through 5 ohms 5 hr per day, 5 days per week B: above discharge through 9000 ohms	A: 1.1 B: 63	BA-48
A. 1.5 B. 67.5 C. -7.5	L. 4-1/8 W. 3-3/4 H. 5-1/4	4, 4	A: through 7.5 ohms B: through 7500 ohms C: through 833.3 ohms for 90 hr, 5 hr per day, 5 days per week	A: 1.1 B: 50 C: -5.5	BA-244/U (2)
A. 1.5 B. 67.5 B_p 135 (3) C. -6	L. 3-5/8 W. 1-13/16 H. 6-1/2	2, 8	A: through 6.5 ohms B: 2 min through 3700 ohms and 2 min through 16,900 ohms B_p: 2 min open circuit and 2 min through 5870 ohms C: 2 min open circuit and 2 min through 200 ohms for 210 min	A: 1.0 B: 45 B_p: 90 C: -4.0	BA-331/U
A. 1.5 B. 45 B_p 90 C. -4.5	L. 3-13/16 W. 2-5/8 H. 5-3/8	3, 0	20 hr in cycles of 2 min and 18 min as follows 2 min — 18 min A: 1.25 ohms — 2.5 ohms B_p: 3750 ohms — 3750 ohms B_p: 2727 ohms — open circuit C: open circuit — open circuit	A: 1.1 B_p: 34.0 B_p: 72 C: [illegible]	BA-370/U
A. 1.5 B. 67.5 B_p 135 C. -6	L. 8-5/16 W. 2-3/16 H. 8-5/16	8, 8	24 hr in cycles of 2 min and 18 min as follows 2 min — 18 min A: 3.53 ohms — 2.13 ohms B_p: 4300 ohms — 2700 ohms B_p: 9000 ohms — 160,000 ohms C: 16.3 ohms — 8000 ohms	A: 1.1 B_p: 59 B_p: 100 C: -4.8	BA-392/U
A. 1.5 B. 90	L. 5-1/4 W. 4-3/32 H. 6-15/16	7, 13	40 hr as follows A: through 1.4 ohms B: 2 min through 1560 ohms and 4 min through 2600 ohms	A: 1.1 B: 65	BA-40
A. 1.5 B. 90	L. 5-1/4 W. 4-3/32 H. 6-15/16	7, 13	Initial: 9 hr as follows: A: through 1.4 ohms B: 2 min through 1560 ohms and 4 min through 2600 ohms Accelerated above discharges for 8.9 hr	A: 1.1 B: [illegible]	BA-2040/U
A. 1.5 B. 90	L. 15-13/16 W. 6-1/2 H. 6-15/16	24, 0	250 hr for 10 hr per day, 5 days per week A: through 3 ohms B: through 6000 ohms	A: 1.1 B: 65	BA-412/U

*Numbers in parentheses appearing throughout table refer to notes on page 347.

Table 7—Multiple Unit Batteries, Electrical and Mechanical Details in Accordance with Specification MIL-B-18B (1) (cont)

Voltage	Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Weight (lb, oz max)	Discharge	Test end voltage (volts)	Type
A. 1.5 B. 90	L. 10 W. 2-3/16 H. 4-7/8	5, 8	Initial: 81 hr for 5 hr per day, 5 days per week through: A: 5 ohms B: 9000 ohms Arctic: 8 hr of above discharges	A: 1.1 B: 65	BA-2048/U
A. 1.5 B. 90	L. 8-1/16 W. 2-3/16 H. 4-21/32	5, 0	90 hr for 5 hr per day, 5 days per week through: A: 7.5 ohms B: 9000 ohms	A: 1.1 B: 65	BA-220/U
A. 1.5 B. 135 (4) B_+ 202.5 (5) C. -1.5	L. 8 W. 6.75 H. 8.5	32, 0	90 days through: A: 8.5 ohms B_1: 9 megohms B_2: 0.5 megohms B_2(tap): 2.7 megohms C: open circuit S: 20,000 ohms (6)	A: 0.9 B_1: 125 B_2: 160 B_2(tap): 31 C: -1.3 S: 10.5	BA-241/U (7)
A. 1.5 B. 180 (8) B_+ 150 (9) C. -8	D. 4 H. 5-9/16 (approx)	4, 8	75 hr through: A: 2.5 ohms B: 170,000 ohms B(130 tap): 360,000 ohms B(67.5 tap): 63,000 ohms B_1: 9000 ohms B_1(tap): 16,000 ohms C: open circuit	A: 1.25 B: 170 B(135 tap): 130 B(67.5 tap): 65 B_2: 153 B_2(tap): 115 C: -8	BA-230/U (10)
A. 1.5 B. 198 (11)	L. 10.312 W. 8.312 H. 6.937	32, 0	90 days through: A: 15 ohms B: 200,000 ohms	A: 1.0 B: 165	BA-238/U (7)
A. 1.5 B. 303	D. 3.25 H. 6.751	3, 0	96 hr through: A: 13 ohms B: 600,000 ohms	A: 1.25 B: 225	BA-345/U
A. 1.5 B. 45 B_+ 90 C. -4.5	L. 2-13/16 W. 2-5/8 H. 7-3/8	3, 0	Initial: 16 hr in cycles of 2 min and 18 min as follows: 2 min / 18 min A: 1.25 ohms / [illegible] ohms B_1: 3750 ohms / 3750 ohms B_2: 2727 ohms / open circuit C: open circuit / open circuit Arctic: 1.6 hr of above discharges	A: 1.1 B_1: 34 B_2: 72	BA-2270/U
A. 1.5 B. 67.5 B_+ 135 C. -6	L. 3-5/16 W. 3-5/16 H. 8-3/16	4, 8	Initial: 19 hr in cycles of 2 min and 18 min as follows: 2 min / 18 min A: 3.59 ohms / 2.18 ohms B_1: 4500 ohms / 2700 ohms B_2: 3000 ohms / 160,000 ohms C: 16.2 ohms / 6000 ohms	A: 1.1 B_1: 50 B_2: 100 C: -4.5	BA-2279/U
A_1: 3 A_2: 1.5 B. 156 C. -7.5	L. 9-3/8 W. 6-9/16 H. 4-3/8	18, 0	25 hr in 15 min periods as follows: 1st period / 2nd period A_1: 7.5 ohms / 10 ohms A_2: 7.5 ohms / 10 ohms B: 5200 ohms / 9000 ohms C: 375 ohms / open circuit	A_1: 2.3 A_2: 1.25 B: 125 C: -6.5	BA-218/U
A. 3 B. 90	L. 4-1/16 W. 1-15/16 H. 4-9/16	1, 5	3.25 hr through: A: 16 ohms B: 7500 ohms	A: 2.2 B: 68	BA-67

Table II—Multiple Unit Batteries, Electrical and Mechanical Details in Accordance with Specification MIL-B-18B (1) (cont)

Voltage	Body dimensions (inches) D. Diameter L. Length W. Width H. Height	Weight (lb, oz max)	Discharge	Test end voltage (volts)	Type
A. 3 B. 135 C_1: -94.5 (12) C_2: 55.5 (13)	L. 3.982 W. 3.438 H. 6.156	3, 6	50 min through A: 8.5 ohms B: 21,600 ohms C_1: 50 megohms C_1(tap): open circuit C_2: 3 megohms C_2(tap): open circuit	A: 2.2 B: 120 C_1: -96.8 C_1(tap): -3.07 C_2: 56.9 C_2(tap): 33.9	BA-271/U
A. 3 B. 90	L. 4-1/16 W. 1-13/16 H. 4-9/16	1, 9	Initial: 2.8 hr through A: 16 ohms B: 7500 ohms Arctic: 0.28 hr of above discharge	A: 2.2 B: 68	BA-2067/U
A. 4.5 B. 25.5 B_2: 60	L. 2-3/8 W. 2-1/8 H. 3-1/2	1, 9	140 hr through 80,000 ohms (14)	68 (14)	BA-41
A. 4.5 B. 25.5 B_2. 60	L. 2-3/8 W. 2-1/8 H. 3-1/2	1, 9	Initial: 112 hr through 80,000 ohms (14) Arctic: 11 hr through 80,000 ohms (14)	65 (14)	BA-2041/U
A. 4.5 B. 90 B_2. 69	L. 10-3/16 W. 4-1/2 H. 7-3/4	16, 0	20 hr as follows A: 2 min through 10 ohms and 4 min through 16 ohms B_1: through 3300 ohms B_1 and B_2 in series: 2 min through 3300 ohms and 4 min open circuit	A: 3.6 B_1: 63 B_1 and B_2 in series: 105	BA-70
A. 4.5 B. 90 B_2. 60	L. 10-3/16 W. 4-1/2 H. 7-3/4	16, 0	Initial: 10 hr as in BA-70 above Arctic: 1.8 hr as above	A: 3.6 B_1: 63 B_1 and B_2 in series: 105	BA-2070/U
A. 6 B. 97.5	L. (15)	7, 0	30 min through A: 5.2 ohms B: 33,000 ohms	A: 3 B: 58	BA-280/U
A. 7.5 B. 120	L. 3-7/8 W. 2-19/32 H. 3-3/8	4, 8	3 hr through A: 19 ohms B: 30,000 ohms	A: 5.25 B: 90	BA-253/U
A. 7.5 B. 150	L. 6-7/16 W. 5-3/4 H. 7-1/16	8, 12	(40 hr: 2 min through following resistances and 4 min open circuit) A: 37.5 ohms B: 3600 ohms	A: 5.5 B: 110	BA-39
A. 7.5 B. 150	L. 6-7/16 W. 5-3/4 H. 7-1/16	8, 12	Initial: 36 hr as in BA-39 above Arctic: 5.0 hr of above discharge	A: 5.5 B: 110	BA-2039/U
A. 7.5 B. 150	L. 6-7/16 W. 5-3/4 H. 7-1/16	8, 12	150 as in BA-39 above	A: 5.5 B: 110	BA-1039/U
A. — B. 43.5 B_2. 22.1 C. 5.1 (16)	L. 3-3/16 W. 1-5/16 H. 4-3/16	1, 4	100 days through 1.25 megohms (14)	70 (14)	BA-1273/U

Notes

1. Batteries have socket terminals unless otherwise noted
2. Stud and nut terminals
3. B_2 unit is center tapped for B_1 unit
4. Tapped at 22.5 and 60 volts
5. Tapped at 40.5 volts
6. 6 volt has nominal voltage of 12 volts
7. Cable and cable connector terminal
8. Tapped at 67.5 and 135 volts
9. Tapped at 135 volts
10. Socket, cable and cable connector
11. Tapped 40.5 and 150 volts
12. Tapped at -3 volts
13. Tapped at 33 volts
14. All units connected in series
15. Irregular shape
16. Center-tapped

INDEX

O

P

R

S

W